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A SIMULATOR INVESTIGATION OF PILOT PERFORMANCE DURING EXTENDED PERIODS OF LOW-ALTITUDE, HIGH-SPEED FLIGHT

by S. M. Soliday and B. Schohan

Prepared under Contract No. NASw-451 *by*
NORTH AMERICAN AVIATION, INC.
Columbus, Ohio
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1964

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For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $2.50

FOREWORD

This study is a part of a NASA investigation of man-machine compatibility under low-altitude high-speed conditions. It was sponsored by NASA under Contract NASw-451 (HS-819), with Mr. Melvin Sadoff serving as NASA Project Monitor.

The study was conducted by the Human Factors Group of North American Aviation, Inc., Columbus, Ohio, under the technical direction of Dr. Stanley M. Soliday and Mr. Ben Schohan.

Acknowledgement and appreciation are hereby extended to the following personnel, who served most cooperatively and well as subjects in the experimental phases of the study.

Major Oliver P. Arquilla, USAF, Fighter Operations Div., ASD, Wright Field, Ohio; Lt. Hugh J. Campbell, USN, NATC, Patuxent River, Md.; Mr. William Dana, NASA Flight Research Center, Edwards Air Force Base, California; Mr. Ronald Gerdes, NASA-Ames Research Center, Moffett-Field, California; Mr. W. J. Potocki, NAA, Columbus, Ohio; Capt. Robert W. Smith, USAF, Edwards Air Force Base, California; Mr. Robert Sommer, NASA, Langley Research Center, Langley Station, Hampton, Virginia; and Lt. Dwight D. Timm, USN, NATC, Patuxent River, Maryland.

Acknowledgement and appreciation are also extended to Dr. Walter Frajola, NAA, Columbus, who conducted the physiological and biochemical phases of the study; and to Dr. George N. Ornstein and Mr. Angelo Verdi, NAA, Columbus, for their contributions to the human transfer function analysis.

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A SIMULATOR INVESTIGATION OF PILOT PERFORMANCE DURING EXTENDED PERIODS OF LOW-ALTITUDE, HIGH-SPEED FLIGHT

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SUMMARY

Eight experienced jet test pilots performed piloting and navigational tasks during simulated low-altitude high-speed (LAHS) flight. The tests were made in a flight simulator that consisted of a vertically moving cockpit having a total travel of approximately 12 feet and an acceleration capability of ± 6G. The simulator had a functional control system and an associated analog computer for obtaining solutions to the equations of motion of a mechanized aircraft.

The experimental flights were made under varying conditions of gust, terrain, and airspeed. Performance and physiological measures were recorded continually during the flights. Blood samples, drawn after certain flights, were studied to determine biochemical effects of the flight stresses.

Pitching errors made by the pilots varied with terrain and airspeed, and increased when the vertical accelerations increased in magnitude. Altitude errors increased steadily as the gust-induced normal accelerations increased. Performance of the navigational task did not vary with terrain, airspeed, or accelerations. Control stick displacement, frequency of control stick movement, heart rate, and respiratory rate varied systematically with several of the experimental conditions. Changes in certain enzymes were detected which were sufficient to warrant further study as indices of LAHS flight stress.

A pencil-type side-stick controller was much more efficient than a conventional center-stick controller in the simulated flights. With the side-stick, task performance errors, total accelerations of the simulator, and heart and respiratory rates were reduced. However, fatigue effects were greater with the side-stick than with the center-stick controller.

Pitch augmentation affected only pitch errors and control stick movements.

Human transfer function coefficients varied with task complexity.

Conclusions were discussed and recommendations made.

INTRODUCTION

Analyses of aircraft penetration missions show that the low-altitude, high-speed (LAHS) mission may provide a superior survival probability over missions flown at higher altitudes. However, these survival studies do not take into consideration the capability of airborne man-machine systems to perform effectively at altitudes below one thousand feet. Aircraft handling and riding qualities in LAHS flight have previously been studied (e.g., Reference 1). In addition to aircraft capability, pilot capability in the LAHS regime must also be determined. This latter capability, particularly the ability of pilots to perform effectively in this environment, is of critical importance to implementation of the LAHS concept.

Sustained low-altitude, high-speed flights pose serious man-machine problems not encountered in other flight regimes. Error tolerances are relatively small in the primary task of controlling the aircraft, thus demanding intense concentration from the pilot. Associated cockpit duties, if required, will compound the task-time loading on the operator. Motion of the pilot's body in atmospheric turbulence incurs problems of visual efficiency, fatigue, variable stick inputs, seat restraint and bodily comfort. These factors tend to reduce the pilot's ability to fly the mission with precision. However, the magnitude of this performance degradation is unknown.

The airplane is also subjected to severe gust loads, to pilot-induced overloads (correction of own errors) and to maneuver loads imposed by terrain following. Thus, the closed loop man-machine system interactions are highly significant in any assessment of LAHS flight capability.

Parts of the overall problem have been studied in the past, e.g., laboratory vibration and fatigue studies. Attempts have also been made to obtain operator psychomotor and physiological data during flight test programs. However, several factors which limited, or at least adversely affected, operator capability under LAHS flight conditions could not be measured in flight test programs because of (1) operator instrumentation difficulties, (2) lack of controlled, predictable environmental conditions (e.g. gusts), (3) lack of controlled experimental conditions, and (4) hazards involved in LAHS flight experiments. Man-machine system simulation is the only feasible technique for overcoming the limitations of flight test programs and isolated laboratory studies in obtaining data to systematically document the interrelationships among system and operator psychomotor performance and physiological response.

This study was conducted to investigate pilot performance and physiological responses under simulated LAHS conditions in a closed loop man-machine flight system, using a motion simulator capable of reproducing gust-induced normal accelerations. More specifically, the objectives were to measure pilot proficiency, vehicle accelerations, and pilot physiological responses in a manned air vehicle system during sustained LAHS flight, and to relate these measurements to aircraft speed, gust acceleration environment, and terrain contour.

METHOD

Subjects

Eight experienced jet test pilots participated in the main experiment. Three were from NASA, two were from the U. S. Air Force, two were from the U. S. Navy, and one was an employee of North American Aviation, Inc. Their ages ranged from 27 to 45, their heights from 5'4" to 6'1", and their weights from 143 to 170 pounds. Jet flying hours ranged from 1500 to 4000 hours, and all had previously had LAHS flying experience.

The Dynamic Flight Simulator (G-Seat)

The dynamic flight simulator used in this study consisted of a vertically moving cockpit having a total travel of approximately twelve feet and the capability of accelerating up to ± 6G, a functional control system and cockpit display and an analog computer for obtaining solutions to equations of motion (Figure A1, page 38; Figure A2, page 39; Reference 26).

Longitudinal control system feel characteristics, such as bob weight forces, viscous damping, and bungee rate, were simulated by using a feel simulator which was simply a hydraulic actuator with feedback from stick rate and displacement, and aircraft load factor and pitch acceleration. Safety and limiting circuits were used to modify the input command to the G-seat servo. The seat is actually a position servo with a ± 6 feet travel. Therefore, a ± 20 volt limiter was incorporated as an electrical stop on seat travel. Frequency response calibrations of the G-seat are given on page 32 of Appendix A and in Figure A3, page 40.

The simulator was equipped with a modified A-5A seat which used the integrated torso harness system of the F9F-8T. Since the system in the G-seat does not incorporate an inertia reel, the operator's shoulders were held rigidly against the back of the seat.

The Mechanized Aircraft

The analog computer was mechanized for five degrees of freedom, as described in Table A1, page 36. Pilots were thus provided physical motion of the G-seat in the vertical axis, and rotational positions in pitch, roll, and yaw were displayed on an all-attitude indicator. Deviations for the equations of motion were supplied by NASA. They are representative of a TFX-type aircraft. Coefficients for the equations of motion are listed in Table A2, page 37. Longitudinal short-period and lateral-directional characteristics of the mechanized aircraft are described on pages 32 and 33 of Appendix A.

The addition of two degrees of freedom over the conventional three was to obtain data on excitation of the dutch roll mode, if it appeared.

Displays

The pilots used information from four functional instruments: a cathode-ray tube (CRT), an all-attitude indicator (AAI), a radar altimeter, and a rate-of-climb indicator. Figure A4, page 41, illustrates the instrument panel layout.

The CRT provided a command error display through movements of one of two luminous horizontal lines on the tube face. One line represented the aircraft, and was stationary; the other line represented the horizon, and was movable. Displayed error was a combination of pitch error and altitude error. Pitch error was the angle between the instantaneous pitch attitude of the aircraft and the terrain slope 2.5 seconds ahead of the aircraft. (Due to this 2.5 second lead time, the pitch error actually represents a projected pitch error.) Altitude error was the deviation from a base altitude of 500 feet above the terrain, and was measured directly beneath the aircraft. Summation of the two errors provided, in one error signal, information about oncoming terrain slopes and present altitude. As long as the correct pitch angle was maintained, the aircraft would be at, or converging on, a predetermined (500 ft) height above the terrain. A displacement of one inch between the moving terrain trace and the fixed aircraft reference was equivalent to 10 degrees of projected pitch error or 400 feet of altitude error. (See Figure A5, page 42, for a block diagram describing the signal flow for aircraft altitude and pitch control.)

The AAI was a standard instrument driven by the computer. As previously noted, it showed all aircraft rotational positions, i.e., pitch, roll, and heading. Although most of the flight information on the dynamic behavior of the aircraft was displayed, it was used primarily to obtain heading information. The radar altimeter presented height directly under the aircraft. Instantaneous rate of climb, computed from attitude angle and airspeed, was displayed on the rate-of-climb indicator.

An electronic G-meter, clock, and mechanical G-meter were also provided. The instrument panel also contained dummy instruments to enhance realism. All instruments were illuminated with red lights.

Controls

Controls consisted of a center-stick controller functional in lateral and longitudinal modes, adjustable dummy rudder pedals, and a microphone switch on a dummy throttle. The control stick was a standard type, with a curved shaft and an offset grip (Figure A6, page 43). It had a longitudinal trim button and an emergency "kill" button which would stop seat motion when pressed. A detailed description of control stick force and displacement characteristics is given on page 33 of Appendix A, and in Figures A7-A10, pages 44-47.

Physiological Apparatus

A NASA-Ames physiological package was installed outside the cockpit on a rigid platform. The package was linked by a cable to a receptacle on the left of the pilot's seat, and by another cable to the recorder and power source. A type R, 8-channel, Dynograph (Offner Electronics) recorder was used to provide continuous trace records from the physiological sensors.

The sensors were attached directly to the pilot's body. Leads from the sensors were connected to another set of leads which were part of a harness worn over the shoulders. The harness leads were gathered into a cable which in turn was led out through a side pocket of the flight suit and plugged into the receptacle at the left of the seat. The harness with intact electrodes could, of course, be worn while a subject was not in the G-seat.

Continuous trace records were obtained for the following variables: two electrocardiograms (EKG), one from sternal and the other from lateral electrodes; a pulse wave, from an ear piece photocell pick-up; a respiratory trace of inspiration patterns from a strain-gauge pneumotachometer, and a second respiratory trace, both of inspiration and expiration, from lateral chest electrodes of an impedance pneumograph. Details of the sensors and their modes of attachment are given on pages 33 and 34, Appendix A.

In addition to the Offner Recorder, an oscilloscope was installed in the experimental room to facilitate medical monitoring of one or the other EKG's.

Blood and Urine Samples

Blood and urine specimens were obtained from the pilots before they reported to the testing facility. The serum so obtained was frozen, stored frozen, and flown or brought to the testing facility in a frozen state along with the urine samples for analysis. Blood specimens were obtained after various experimental flights; these specimens were allowed to clot, centrifuged, and stored frozen until analyzed. Urine specimens were also obtained at the testing facility.

Experimental (Independent) Variables

Gusts. To simulate LAHS buffeting, gust data were used with acceleration time-histories of root mean square (RMS) gust velocities of 2, 10, and 20 ft/sec.

The 2 ft/sec level provided a base-line condition (real world probability = .885 of the RMS gust being $\leq$ 2 ft/sec); 10 ft/sec represented the maximum real world intensity ($p <$ .001 of the RMS gust being $\geq$ 10 ft/sec); and the 20 ft/sec level, even though unrealistic in flight except, perhaps, in thunderstorms, was chosen because it provided a high degree of acceleration stress. A level as high as 20 ft/sec was necessary because of the low gust sensitivity of the mechanized aircraft (it had 1/2 to 1/3 of the sensitivity of a standard fixed wing subsonic fighter).

Recordings were made of the actual RMS gust input to the seat and of the resulting RMS G loading for each gust-airspeed combination that was used as an experimental condition. These recordings were made with the control stick fixed and with a 180 pound weight in the seat. They are listed on page 35 Appendix A. A discussion of pertinent details of methods used to obtain the gusts is included in this section of Appendix A.

<u>Terrain</u>. Experimental flights were made over two types of terrain: contour (C) and level (L). The C terrain represented rolling desert terrain which varied ± 250 ft. from a median base level, with a maximum slope of ± 5 degrees. The tracking task over L terrain was created in two ways: first, pitch disturbances were caused by inadvertent control stick inputs and by inaccurate corrections of existing error. Second, the gusts themselves caused slight pitch changes when they acted on the aircraft equations, and, in addition, there was a slight computer drift in pitch.

C terrain and gusts were both recorded on the same magnetic tape. The tape took about 55 minutes to run. The terrain was repeated every 20 minutes on this tape, while the gust patterns were randomized through the 55 minutes. In flights over C terrain, signals from the terrain and gust records were both picked up by the computer. In flights over L terrain, gust signals only were picked up by the computer. Both the gust and terrain inputs were the same as those used in Reference 1.

<u>Airspeed</u>. Airspeeds of Mach number 0.9 and 1.2 were used in the study. The terrain tape was run at the same speed for both Mach numbers so that, physically, this would mean that the terrain for 1.2 M would be more gentle than the terrain for 0.9 M (lower slopes due to greater distances from peak to peak). However, for this experiment, an identical tracking task was produced for both Mach numbers, with only a change in aircraft response characteristics serving to differentiate the two airspeeds; the aircraft at 1.2 M was quicker in the longitudinal short-term frequency response and it damped out slower than at 0.9 M.

Experimental Design

The two airspeeds, three gust levels, and two types of terrain were combined into a 2 x 3 x 2 factorial design. The resulting twelve different conditions are summarized in Table A3, page 37. Each pilot was to make a flight under each of the twelve conditions. The conditions were presented randomly to the pilots to control order effects such as learning and fatigue.

All of the flights lasted for one and one-half hours. All flights were made at a constant speed, e.g. if a flight were made at 0.9M, the entire 1 1/2 hours were flown at that speed. The pilot was required to fly continuously during the 1 1/2 hours, except for a 3-4 minute break that occurred about 55 minutes from the beginning. This break was required to rewind the gust and terrain tape. While undesirable from an experimental point of view, this pause probably did not give the pilot enough rest to allow recovery from fatigue (see page 17).

An intercommunication system allowed pilot, experimenter, G-seat operator, and computer personnel to talk among themselves at any time during a mission. Discussion was limited to topics pertinent to the conduct of the experimental flights.

Tasks Required of the Pilot

The experimental flights were organized into simulated missions. During each mission, two principal tasks were required. They were the following:

Pitch Angle and Altitude Hold. The pilots' primary task was to null the error displayed on the CRT. The pitch command signal, represented by a long horizontal line, would move relative to a fixed short horizontal line (aircraft) on the scope. Displacement of the signal above or below the fixed line denoted that the aircraft was pitched higher or lower than desired. Appropriate control stick inputs by the pilot would move the signal to the fixed line, thus maintaining the desired pitch angle. The system worked like an attitude indicator in that the fixed aircraft should be flown to the horizon.

Heading. The pilot was instructed to maintain a 360° heading during the first, middle, and last fifteen minutes of flight. However, he had to monitor this heading, because a pseudo spiral divergence was introduced in the form of a constant heading drift. (Note: The drift was 2° per minute, but the pilot was not given this information.) The heading drift appeared on the AAI, and was to be corrected whenever it became noticeable.

The remainder of the mission was divided into 9 segments of 5 minutes each, with each segment containing a heading change (turn). When a turn was required, it was called out to the pilot by the experimenter, who was acting as navigator. The size of the turns ranged from 5 to 40°. Although individual turns varied in size and direction within a given mission and from mission to mission, the total degrees turned in each of the other missions, and the number of different directions (left or right) was the same in all missions. Size and direction variations in turn patterns were used to prevent memorization of a particular pattern.

Testing Schedule

The testing period lasted two weeks for each pilot. Two pilots were at the testing facility at a given time, arriving at the same time, and leaving at the same time. On the first day of duty, pertinent details of the study were discussed with the pilots and they were given a physical examination.

On the second day of duty, each pilot was given a series of training flights in the G-seat consisting of short flights under all of the conditions to be encountered in the experiment. Physiological measurements were made during the training session.

On the day after the training session, the experimental flights began. Three flights were made each day. This resulted in two flights in a given day for one pilot, and one for the other that same day. In order to have both pilots finish all of their twelve flights on the same day, the pilot who made two flights one day made one the next day, etc.

No attempts were made to control the subjects' activities outside the testing facility other than asking them to refrain from excessive amounts of tea, coffee, ice cream, and bananas for a few hours before a blood sample was to be drawn.

Recorded Data (Dependent Variables)

Performance Measurements. Performance data were recorded by two six-channel pen recorders. Deviations from the bias altitude of 500 feet were integrated each minute as RMS altitude error (He). The instantaneous differences between the actual pitch altitude of the "aircraft" and the terrain slope 2.5 seconds ahead of the aircraft were integrated each minute as RMS pitch error (Pe). Longitudinal control stick displacements were recorded continuously on one recorder channel and integrated each minute as RMS longitudinal stick displacement over another (RMS st). Individual accelerations at the pilot's seat were also continuously recorded on one recorder channel and integrated each minute over another (as RMS G). Average values per minute of transfer function coefficients lag (τ) and gain ( ) of a synthesized pilot plus control stick transfer function were recorded (see page 20 for a description of the form of this transfer function).

A continuous trace of the terrain and actual flight path over it was also obtained. Altitude maintained at any point in the mission can be determined from this trace. Traces of the actual error displayed on the CRT, heading, and lateral control stick displacements were recorded continuously on each of three recorder channels. Table A4, page 37, summarizes all of the recorded measurements.

Figures A11 and A12, pages 48 and 49 are examples of the types of performance records obtained. Measures on each channel are identified on the records. They are from about 3 1/2 minutes of one of the flights, and are read from right to left.

Treatment of Performance Data. Due to the relatively large number of variables recorded in each flight, and to the number of flights made, it was not practical to tabulate scores for every minute. Therefore, a sampling procedure was followed. Scores were tabulated for each minute of minutes 11-15, 36-40, 61-65, and 85-90 in each flight. This produced a sample of twenty scores for each variable. The first and last five-minute periods contained no turns, while the two middle periods each contained one turn. The proportional number of turns in the sample was then 2/20, which matched the proportional number of turns in the entire flight (9) to the number of minutes in the entire flight.

To determine the validity of this sampling procedure, scores were first tabulated for all ninety minutes for all of the measured variables on several different flights. Means and standard deviations of these scores were then compared to the means and standard deviations that would have resulted from the sampling procedure. Agreement between the two sets of scores was excellent. In addition to this comparison, it was found that no consecutive five-minute terrain and gust sample differed significantly from any other consecutive five-minute sample in terms of number of peaks and valleys and steepness of slopes, and in terms of severity of gusts. In this connection, it was also determined that the reliability of all measurements was excellent.

Physiological Measurements. For each of the simulated flights, the average heart rate and average respiratory rate were determined by examination of the physiological tracings. At the beginning and end, and at five to ten minute intervals during the flight, the number of heart beats and respirations in a one-minute time period were counted. Because respiration caused simultaneous changes in the impedance pneumograph and pneumotachometer tracings, a comparison of the two was possible by calculation of the areas under their respective curves. Measurements during several one-minute intervals in a given flight were used to calculate the averages. Figure A13, page 50, is an example of a typical physiological tracing. Identification of each channel is made on the tracing. The record is read from left to right.

Biochemical Measurements. Enzymes measured included glutamic-oxalacetic transaminase (GOT), glutamic-pyruvic transaminase (GPT), lactic dehydrogenase (LDH), malic dehydrogenase (MDH), aldolase (ALD), leucylaminopeptidase, (LPD), phosphohexose isomerase (PHI), acetylcholinesterase (ACE), and alkaline phosphatase (ALK PH). Cholesterol levels and percentage cholesterol esters were determined on some of the specimens.

Pilots' Comments. Pilot's documented comments are presented in Appendix E, pages 85-91.

Urines were analyzed for 17-ketosteroids (17 KS), 17-hydroxycorticosteroids (17-OHCS), and vanillomandelic acid (VMA). Because the analysis was difficult and because of a possible inactivation of the enzyme used in the analysis that made their results questionable, 17-OHCS were not measured on the later specimens. Since creatinine excretion is normally constant for a 24-hour period, a low value is indicative of an incomplete collection. Creatinine analyses were, therefore, added to overcome the difficulty of incomplete urine collections. This was done by calculating excretions of other substances per gram of creatinine.

RESULTS AND DISCUSSION

Although 96 flights were planned, several were lost due to the reassignment of one subject pilot after one of the two scheduled weeks, the discontinuation of half of a flight schedule for another after an apparently abnormal EKG was recorded in a flight (see page 15), and occasional equipment failures. Since subjects were unable to return to the testing facility after their two weeks, lost flights could not be made up. These results are, then, based on a total of eighty flights. Difficulties with individual recording channels sometimes caused losses within these eighty, and so the number of measurements actually used in the various statistical tests can be determined from the associated degrees of freedom.

Throughout the rest of this report, abbreviations for the twelve experimental conditions are used. An abbreviation consists of a number followed by a letter which is in turn followed by a second number. The first number refers to the RMS gust level, the letter to the type of terrain, and the second number to the airspeed; e.g. in 20C12, the RMS gust level is 20 ft/sec, the terrain is contour, and the airspeed is 1.2 Mach number.

Measured Acceleration Environment

G Loadings Associated with Each Flight Condition. Accelerations from the pilot's seat were measured by an accelerometer attached to the seat. RMS G was recorded each minute. Average (mean) values of the RMS G were computed for each individual flight, and then mean values of this measure were determined for each flight condition by averaging the mean values with each condition. The latter means are listed in Table B1, page 51 . Peak G's, which show the G range at each condition, are also listed. There are marked G increases associated with gust level increases. G is higher at 1.2 than at 0.9M, and is generally higher in flights over contour terrain. Peak G's are higher at the higher gust levels, and are higher at the higher airspeed. However, there is very little difference in peak G's between contour and level flights.

Total G at the beginning of flights was compared to total G at the end to determine if it increased over time. No significant beginning-end differences were found; therefore, G experienced by the pilots did not change as a function of time.

Maximum RMS G's were measured in condition 20C12. The mean RMS G level in this condition was .2910, a value that is about 30 percent over the tolerance boundary established in previous studies (References 1 and 29). Although the maximum RMS G's in the present study are in the "intolerable" acceleration region, performance errors did not increase over the ninety minutes (see discussion under Fatigue, page 16). Further, the pilots did not report being unduly stressed, or even that they were fatigued after ninety minutes at the highest G levels. Some of the pilots did mention vision blurring at the 20 ft/sec gust level, but there were no reports that it increased from beginning to end of flights (see Pilots' Comments, Appendix E, pages 85-91).

Comparison of Actual and Total G. It is of interest to compare the RMS G loadings described above ("Total G") with RMS G loadings obtained when a 180 pound weight was in the seat and the control stick was fixed ("Actual G"). These comparisons are listed in Table B2, page 51. There is a definite tendency for total G to become relatively less as G commands from the computer (actual G) increase in magnitude, i.e. pilots maneuvered in such a way as to subtract from the command G rather than add to it. This procedure undoubtedly increased the comfort of the pilots at the higher G levels.

Pilot Performance Measures

Pitch, altitude, and heading errors were used as performance criteria.

Pitch Error (Pe). Mean values of RMS pitch error (Pe) were computed for each individual flight, and then mean values of this measure were determined for each flight condition by averaging the mean values within each condition. The latter means and their standard deviations are listed in Table B3, page 52.

An analysis of variance was performed on these scores. There are highly significant main effects for all three variables ($p < .001$ in all three cases), and two significant interactions (airspeed by terrain, $p < .001$; and gust by terrain, $p < .01$). (Homogeneity of variance was indicated by a Bartlett's test; $\chi^2 = 16.0887$, $d_f = 11$.) Results of the analysis of variance are summarized in Table B4, page 52.

Individual mean differences were tested for significance with Duncan's Multiple Range Test.[1] All mean differences between level and contour flights are significant; there are 80 percent more pitch errors in flights over contour terrain. In the terrain following mode, there would, of course, be more

[1] From Edwards, Allen L., Experimental Design in Psychological Research New York: Holt, Rinehart, and Winston, 1962 (Revised Edition).

and greater pitch attitude changes when the aircraft flies over contour than when it flies over level terrain since contour terrain, by definition, undulates more than level terrain.

Airspeed differences show a more complicated pattern than terrain differences. In flights over level terrain, the only significant airspeed differences are between 20L9 and 20L12, where there are 23 percent more errors at 20L9. In flights over contour terrain, however, there are significant differences between the two airspeeds at all gust levels; with an average of 19 percent more errors at 0.9M. This pattern can be seen in Figure B1, page 64 which shows a sharp decrease in error from 0.9 to 1.2M in flights over contour terrain, and a very small error decrease from 0.9 to 1.2M in flights over level terrain.

Figures B2 and B3, pages 65 and 66 show pitch errors as a function of RMS gust level. Figure B2 shows the two airspeeds at each of the two terrain types, while Figure B3 shows only the two terrain types. In flights over level terrain, there are no significant Pe differences between the 2 and 10 ft/sec gust levels at either airspeed, and there are no significant differences between 10 and 20 ft/sec gusts at 1.2M in the L flights. However, there are significantly more pitch errors at 20L9 than at 10L9, (55 percent more at 20L9). This pattern can be seen in both Figures B2 and B3, but most clearly in Figure B3, where there is a fairly sharp error increase between the 10 and 20 ft/sec gust levels in the L flights.

Gusts affect flights over contour terrain differently from flights over level terrain. In the C flights at 1.2M, differences between all of the gust levels are significant. Here, G increased Pe 12 percent from 2 to 10 ft/sec gust levels, and 10 percent from 10 to 20 ft/sec gust levels. In the C flights at 0.9M, however, there are no significant differences between 2 and 10 ft/sec but there are significantly more errors at 20 than at 10 ft/sec (7 percent more). Although G affects the pilot's control at 1.2M throughout the range tested, it should be observed that pitching error is consistently greater at 0.9M.

<u>Altitude Error (He)</u>. Deviations from 500 ft. altitude were recorded every minute as RMS He[2]. Mean He values were computed for each individual flight, and then mean values of this measure were determined for each flight condition by averaging the mean values within each condition. The latter averages, and their standard deviations, are listed in Table B5, page 53.

The only significant differences between the conditions are between the gust levels; the F-ratio is significant beyond the .05 level of confidence (see Table B6, page 53). Altitude errors increase consistently as gust level increases. Differences between 2 and 10 ft/sec are significant beyond the

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2 Although average altitude error was not recorded as a separate variable, it was measured from the flight path-terrain trace of several different missions. In all cases, average He was zero or approximately zero. Justification for treatment of the RMS scores as standard deviations or reasonable approximations of standard deviations is thus provided by this evidence.

.025 level, and differences between 10 and 20 ft/sec are not quite significant. Differences between 2 and 20 ft/sec are, of course, highly significant ($p < .005$). Figure B4, page 67, which shows He as a function of G, shows that He increases steadily as G increases. The rate of He increase is about 25 per cent per 0.1 RMS G.

The absence of He differences between contour and level flights is probably due to a combination of two factors. First, the CRT terrain presentation, designed to provide time for the pilot to respond to a given slope before he was directly over it, was effective. Second, the contour terrain was itself relatively mild. Differences might have appeared between C and L flights if a less appropriate lead time had been used, or if the slopes had been steeper (rougher terrain).

Heading Error (Hc). In addition to turns called out by the experimenter, the constant heading drift introduced into the equations of motion also caused departures from an assigned heading. The magnitude of the drift-caused departures depended on how quickly the pilot perceived a given drift (on the AAI), and how efficient his corrective actions were. Since the rate of drift was constant in all of the experimental conditions, differences among the conditions would be due to the influence of the experimental variables on the pilot. The drift-caused departures represent heading errors, and are performance criteria for the heading task.

The recorded trace of these errors appears as a series of fairly regular gradual deviations from the assigned heading line. Each departure ends with a rather rapid return to the assigned heading line. The areas under the curves thus formed were measured with a planimeter to provide quantitative error scores. Mean errors per minute were determined for each flight, and then mean errors for each experimental condition were determined by averaging the means within each condition.

An analysis of variance yields no significant main effects or interactions. Therefore, it is concluded that there are no differences in heading error due to the experimental variables. (See Table B7, page 54 for a list of the heading errors, and Table B8, page 54 , for a summary of Hc variance). Since there were no differences in heading error, lateral stick movements were not studied.

Reduced to its perceptual essentials, the heading task required a discrimination of visual differences, i.e., differences between vertical lines on the AAI. Although some - but not all - pilots reported vision blurring at the highest gust levels, the blurring evidently was insufficient to affect heading task performance because, if it had, there would have been differences in heading error as a function of G. Of course, there were performance changes on the altitude hold task that were correlated with G. However, there appears to be no reason to assume that blurring affected performance in this case, even though the CRT lines were in a different plane than the AAI lines (horizontal rather than vertical). It seems more likely that the type of controller and the degree of restraint of inadvertent control stick inputs have the greatest affect on error production and reduction in this particular acceleration environment (see the side-stick controller evaluation section, pages 22-25.

Physiological Measures

The present study originally included a G-seat validation phase whose purpose was to compare physiological responses made in actual LAHS flight with the same kinds of responses made in the G-seat. In the simulated flights, the G-seat was to have been programmed with the acceleration time-histories recorded during the actual flights, and each pilot who flew the actual flights would fly the G-seat with the acceleration time-history corresponding to the one recorded in his actual flight. However, when the flight test physiological data were analyzed, it was determined that the data would not permit meaningful correlation with the physiological measurements that would have been taken on the G-seat. The study was therefore reoriented; the validation phase was deleted and a more systematic evaluation of the side-arm controller was made.

Except for one pilot, with whom difficulty in electrical grounding was experienced, the electrocardiograms were good. Pulse wave measurements were not satisfactory. Respiration rate and volume were successfully monitored with the pneumotachometer. However, impedance pneumograph monitoring of these two parameters was very erratic; on many occasions no tracings at all were obtained. Analysis of the areas under the curves as a reflection of the tidal volumes for the pneumotachometer and for the impedance pneumograph indicated wide variations without correlations for any of the conditions of the simulated flights.

Table B9, pages 55-57 , gives average heart and respiratory rates for each of the simulated flights, categorized by pilot and experimental condition. The average heart rates ranged from 75 to 94 beats per minute; the respiratory rates, from 8 to 24. These values are indicative of mild excitement or anxiety, but are within normal limits for active subjects. The Russians reported that their cosmonauts Bykovsky and Tereshkova registered fluctuations in pulse frequency from 46 to 80 and 58 to 84, respectively, and fluctuations in respiration from 12 to 22 and 16 to 22 respirations per minute, respectively (Reference 32). Astronaut W. M. Shirra, Jr., exhibited wide fluctuations in heart rate in tests at the Lovelace Clinic from 68 to 160 beats a minute with a mean of 96. Throughout simulated flights and countdown his heart rate ranged from 43 to 88 whereas in flight and post flight measurements, it varied from 56 to 121 beats per minute (Reference 2).

No significant differences were found on an analysis of variance of heart rates. However, examination of Table B9 reveals that, for each pilot except #8, the mean heart rate for contour flight was greater than for level flight. It should be noted that more work was done in contour than in level flight; there was 27 percent more control stick movement in the contour flights.

The pilots breathed faster at the 10 ft/sec gust level (RMS G = .138) than they did at the 2 ft/sec gust level (RMS G = .045). There were 16.8 inspirations per minute at the 10 ft/sec level, and 14.9 inspirations per minute at the 2 ft/sec level. There were no significant differences between the 20 and the 10 ft/sec levels (there were 17.6 inspirations at the 20 ft/sec level). There were no other significant main effects for respiration rate, and no significant interactions. Apparently, the rate of breathing increases rapidly at first with G increases up to about RMS .14, and then increases slower after that.

Biochemical Measures

In one instance (pilot #1) a simulated flight schedule was discontinued because of an apparently abnormal electrocardiogram. Blood specimens were obtained at intervals of several hours for assay of cholesterol and the enzymes reflecting muscle stress (GOT, GPT, and LDH). Very minor increases were noted in the total cholesterol level and in the GOT activity (270 to 291 mg./100 ml. and 23 to 33 units, respectively). Further clinical evaluation and examination of the tracings together with the data of subsequent simulated flights indicated that the medical monitor may have been more cautious than necessary.

Table B10, page 58 , presents the results of the analyses of the urine obtained from pilots before and after their simulated LAHS flights. In order to properly assess the completeness of the 24-hour urine collections, creatinine was assayed in each specimen. By calculating the catecholamine and 17 KS excretion per gram of creatinine, errors resulting from incomplete collections were reduced. No apparent increase in catecholamine excretions as a result of simulated LAHS flight occurred.

Increased serum cholesterol levels indicative of reaction to stress did not occur except for the incident reported above (pilot #1). It appears, however, that of the pilots tested, only one (pilot #2) had cholesterol levels consistently within the normal range (see Table B11, page 59). This may be interpreted to mean that the pilots were in a stressed condition (their ordinary flight activities before coming to NAA) before they began the simulated flights. The cholesterol level of Pilot #8 was sufficiently above normal that he was advised to seek further examination and medical advice.

Several serum enzyme activities were measured before and after the flights (Table B12, page 60). No significant changes were observed in the GOT, GPT, LDH, MDH, or ALD activities. A slight increase in the GOT activity of Pilot #1, although indicative of a potential relationship, was not considered important. Alkaline phosphatase activity used in clinical practice to detect liver damage or bone disease was elevated in several instances.

A tendency toward increased ALK PH activity was noted in two pilots, although the correlation was not statistically significant. This enzyme system warrants further investigation as an index of stress.

PHI and LAP activities varied considerably. Consistent depression of PHI or LAP activity was not observed. In one instance (PHI, Pilot #3), a ten-fold increase was noted. Further experimentation is required to properly understand the role of these two enzymes relevant to LAHS flight conditions.

In any attempt to assess the degree of stress produced by simulated LAHS flight by measurement of serum enzyme activities, several factors should be considered. Of initial importance is the problem of the treatment of the serum on collection. Does freezing the serum and storing it frozen for varying periods of time have the same effect on the enzyme activity present whether the enzyme was present initially in great amounts or only in minor amounts? Is the stress condition great enough (sufficient degree, duration, or type) to produce a change in the enzyme activity? What is the correct time interval after the stress to obtain the blood specimen for detection of the change in the enzyme activity? The results obtained in this study indicate that the stress of LAHS flight may not be sufficient to alter the activity of several enzymes: GOT, GPT, LDH, MDG, and ALD; but that ALK PH, LAP and PHI may be affected.

Fatigue

Study of possible fatigue effects was made by comparing error scores at 11-15 and 85-90 minutes with t - tests. Results for each of the performance measures are given below.

Pe. Error increases appeared in only four of the twelve conditions and error decreases in none. Three of these four conditions were at the lowest gust levels (see Table B13, page 61). These differences probably reflect boredom and consequent inattention rather than fatigue since much greater physical effort in bracing and keeping in position in the seat is needed at the higher gust levels. The boredom hypothesis is strengthened by pilot's comments; they all found the 2 ft/sec runs tedious.

He. Error increases occurred in only 3 of the 12 conditions, and error decreases in none (see Table B14, page 61). The three conditions that show increases are in each of the three acceleration levels. He probably does not show the same pattern of increases that Pe shows because it is generally less responsive to the experimental conditions than Pe. Boredom is probably the cause of the increases at the two lower gust levels. However, the increase at the highest gust level may reflect fatigue since it was one of the most strenuous of the experimental conditions. Nevertheless, it is assumed that fatigue did not play an important role in the determination of He.

Hc. There were no beginning-end changes in this parameter.

RMS St. Significant increases occurred in stick displacement in 5 of the 6 contour flights, but in none of the level flights (Table B15, page 62). The average increase is 27 percent. This pattern seems noteworthy in view of the much greater Pe in the contour as opposed to the level flights, and in view of the fact that there is significantly more displacement (27 percent) over contour than over level terrain. (It is quite coincidental that both average increase and greater displacement over contour terrain average 27 percent.)

Although the few beginning-end increases in pitch and altitude error are not ascribed to fatigue, the pattern of increase in amounts of displacements in contour flights, when compared with level flights, cannot be dismissed as due to boredom or unknown factors. Since the physical effort involved in moving the control stick was 27 percent greater in the contour than in the level flights, the increases in displacement were a reflection of fatigue. The same fine control stick adjustments that must be made at the beginning of a flight must also be made at the end. If muscular fatigue occurs, the movements in making the adjustments will not be as efficient after as they were before its occurrence because of irradiation, a process which results in larger groups of muscles being brought into play to accomplish the same goal. Results of this irradiation process may not be reflected in a criterion measure (e.g. pitch and altitude errors), but may be reflected in the movements themselves as an increase of movement caused by the action of large muscle groups in a situation where the action of smaller muscle groups is adequate. For these reasons, the best explanation of the increases in stick movement in contour flights is that they occurred because of muscular fatigue.

In this connection, it is important to note that pilots rarely, if ever, reported feeling tired after the contour or any other missions. The muscular process described above would not necessarily be felt as a general tiredness because it can represent a localized fatigue that is not necessarily noticeable, or, if it is noticed, may be quickly dismissed as unimportant.

St F, lag, gain. No increases and no decreases over time were noted in any of these parameters.

The pilots' motivation could have increased near the end of the run because of their knowledge that termination was imminent. Increased motivation could have counteracted existing fatigue effects. To investigate this possibility, error scores at the beginnings of runs were compared to scores at the middles. There were no significant differences; therefore, the "motivation" hypothesis was abandoned. In addition to these tests, a comparison of error scores on either side of the 3-4 minute tape rewinding break was also made to determine whether or not any rest gained during the break could have led to recovery from fatigue. There were no significant differences between these two sets of scores. The break was then discounted as a producer of recovery from fatigue.

Fatigue Conclusions. Fatigue was unimportant in error determination, but there was evidence of its appearance in a decrease of efficiency of control stick displacement. Extension of the length of the missions, or an increase in task difficulty, could lead to degradation of criterion measures.

Effects of Turns on Criterion Measures

It was hypothesized that the turns would increase Pe and He scores. Scores during minutes with turns were compared with scores made during minutes without turns. The hypothesis was not verified, and, in addition, there was no indication on the records of a sudden Pe or He increase that could be associated with turns. Turns were thus discounted as a source of error.

Intercorrelations of Various Measures

Intercorrelations Among the Criterion Measures. The means of Pe, He, and Hc were correlated with a Spearman rank order correlation coefficient (rho). To obtain the ranks, the lowest mean score for a particular variable was assigned rank 1, the next higher rank 2, etc., to the highest score which was assigned rank 12. No significant correlations were found (Pe-He, rho = .28; Pe-Hc, rho = .29; He-Hc, rho = .04). This is expected in the Pe-He correlation because both airspeed and terrain markedly affected pitching but not altitude holding. Similarly, in the case of the Hc correlations, Hc was not affected by any of the variables and, therefore, no significant Pe and He correlations were expected.

Intercorrelations Among Criterion and Associated Measures. Mean values of the following variables associated with task performance were determined for the twelve experimental conditions: RMS inches of longitudinal control stick displacements (RMS St), the number of times per minute that the stick was moved from fore to aft and vice versa (StF), average seconds of pilot's lag (τ) per minute, and average pilot's gain (K) per minute. These means are listed in Table B16, page 62. Spearman rhos were determined by correlating the means of the twelve conditions. As with the criterion measures, the lowest mean score of a variable was given rank 1, etc., to the highest mean score which was given rank 12. The correlations are listed in Table B17, page 63.

Significant positive correlations were found between RMS St and Pe (.55, p = .05) and He (.70, p = .05), showing that increasing amounts of both kinds of error are associated with increasing amounts of stick movement. This is expected since more stick corrective movements are needed to compensate for increasing amounts of error. There is also a significant positive correlation of RMS St and St F (.66). This shows that the increased amounts of stick displacement have a frequency as well as amplitude component.

Pitch error shows no correlation with G. This is probably due to the fact that terrain influenced Pe much more than the other two experimental variables; that is, G varies regularly with varying gust and airspeed independent of terrain, while Pe varies largely with contour terrain.

There is a significant positive correlation of He and G (.86, p = .01). This is expected because the analysis of variance shows a very consistent increase of He with G increase.

The correlation between RMS St and G is very high (+.90, p = .01). Again, this is expected because inadvertent stick inputs are caused by G changes; when G increases, inadvertent stick inputs should increase. St F is also positively correlated with G (.64, p = .05), which shows that the frequency of fore and aft movements increases as G increases.

Heading measurements were not significantly correlated with any of the other variables. This parallels the finding of no differences with the analysis of variance. Neither lag nor gain are significantly correlated with any of the other variables, or between themselves, thus being, at least with the correlation technique used, insensitive to the experimental conditions.

Intercorrelations Among Performance and Physiological Measures (Psychophysiological Correlations). Spearman rhos were used to correlate mean heart and respiratory rates with the performance measures. Heart rate is significantly correlated with both Pe (+.60) and He (+.53), and with G (+.56). While it is fairly straightforward to view G as causing error, it is not straightforward to view heart rate as causing error. However, in the latter case, the possibility of a causal relationship must not be overlooked. Increased heart rate is a reflection of increased activity in the autonomic nervous system, and this activity can modify many bodily responses including responses of the skeletal musculature. Increased tension of arm muscles could, for example, interact with the inadvertent G-induced control stick movements in such a way as to increase error, or the increased tension could affect voluntary movements of the operator in such a way as to increase error also.

Respiration rate was significantly correlated with G (+.73) and with He (+.69). Increased respiratory rate is also an indication of increased autonomic activity, and the same reasoning applies with it that applies above.

EFFECTS OF CHANGES IN VEHICLE DYNAMICS

A series of flights was made under simulated pitch augmentation conditions. The augmentation was achieved by increasing the M_q and M_α coefficients of the equations of motion. Two cases of pitch augmentation were investigated: first, a case where M_q and M_α were increased by factors of 3.5 and 2.0, respectively, and second, a case where M_q and M_α were increased by factors of 2.21 and 1.74, respectively. The longitudinal characteristics for the augmented case are compared with the basic airplane in Figure A7, page 44, and are tabulated as follows:

	Pitch Aug.	$3.5\ M_q$, $2.0\ M_\alpha$	Pitch Aug.	$2.21\ M_q$, $1.74\ M_\alpha$
Parameter	M = .9	M = 1.2	M = .9	M = 1.2
f_n - cyc/sec	1.005	1.52	.927	1.40
ζ	.517	.472	.387	.35

During the first case of augmentation simulation, a pitch augmenter failure was simulated by the experimenter's instantaneous switching out of the factors that increased M_q and M_α, so that the coefficients returned to their basic values. The experimental condition for this simulation was 10C12. The flight lasted for 90 minutes, and consisted of periods of flight with the factors increased (augmenter on), then switched out suddenly and allowed to remain that way for a period of time (augmenter off, the basic condition), etc. Four of these augmenter "failures" were programmed during the flight.

Pe, He, G, and RMS St were scored for each minute of the entire flight. The measures were then segregated into two groups, one group representing the "augmenter on" configuration and the other representing the "augmenter off" configuration.

No significant differences are found between He in the two configurations, and there are no significant differences attributable to G. Pe is lower with the augmenter on than with the augmenter off; the differences are significant beyond the .025 level of confidence. There is .69° RMS pitch error per minute in the augmented case as compared to .80° RMS pitch error per minute in the non-augmented case.

There is more stick movement with the augmenter on than with it off; these differences are significant beyond the .005 level of confidence. The stick was moved, both fore and aft, .254 inches per minute with the augmenter on, and .153 inches per minute with the augmenter off.

There was nothing on the flight record to indicate increasing error at the failure points, i.e. points where the M_q and M_α factors were changed.

The second case of augmentation simulation consisted of 15-minute flights with M_q and M_α increased to the values previously described. Augmenter failures were not simulated. According to the pilot, this augmented configuration was indistinguishable from the first.

In summary, the basic airplane was only marginally unsatisfactory, so that even though the pitch augmented tests showed improved longitudinal characteristics, as would be expected, the actual failure of the augmenter caused no serious control problem. The pilot noticed that the changes from the damped to the undamped mode were felt mainly in a slight change in characteristics of the display, and also to a small degree in seat movements. Pilot-induced oscillations were never present.

PILOT DYNAMIC RESPONSE

A special series of five minute flights was made by four of the pilots in order to investigate variations of the operator's transfer function (TF) in response to different tasks. Analysis of the TF data is a preliminary attempt to extract pilot TF information in a somewhat more complex task situation than has been considered in previous studies. Generalization of the obtained results is additionally restricted by the simplified transfer function that was used, viz.,

$$TF = \frac{K}{1 + \tau s} e^{-2.5} .$$

A more valid TF form would have included an additional lag term plus a lead term. Implementation of the more complex form would have required G-seat rescaling, which was beyond the program's scope (the TF "residual" was not measured for the same reason). The results must therefore be considered tentative and the analysis suggestive rather than definitive.

TF comparisons were made with three different tasks at the 10C1.2 experimental condition. The tasks were:

(1) Pitch only (P) - no cockpit motion, pitch tracking;

(2) Pitch and motion (PM) - cockpit motion with simulated gusts, pitch tracking; and

(3) Pitch, motion, and heading (PMH) - cockpit motion with gusts, pitch tracking, heading tracking (with occasional heading change instructions).

Of particular interest were the effects of the three tasks on the gain (K) and lag (τ) coefficients of the TF. Figures C1 - C3, pages 69-71, present the values of τ, K, and ϵ (integrated total error), respectively, for each pilot as well as the group mean for each of the three tasks. See page 68, Appendix C, for details of the TF synthesis and scoring procedures.

The average value of τ for the pitch only (P) condition was -0.1259 sec. (equivalent to a nominal value of zero), whereas for the pitch and motion (PM) condition, it was 0.3805 sec. (see Figure C1). Thus for the PM condition, the operator introduced a lag component in his TF which was not effectively present during the P condition.

It is hypothesized that the increase in the gain K for the PM condition, as shown in Figure C2, reflects the operator's attempt to counteract the normally adverse effect on error of an integral lag. The increase in gain had the effect of increasing the slope of the output of an integral lag filter (Reference 14). This is illustrated in Figure C4, page 72, where the output of the same (integrating) filter to a ramp function is shown for high and low gain systems. Comparison of the high and low gain error correction curves in this figure shows that increased gain tends to reduce the adverse effect of lag on system error by increasing the rate of error correction.

The total integrated error (Figure C3) averaged over subjects for the P condition is 0.069 square inches, whereas for the PM condition ϵ equals 0.097 square inches. The PM task has, of course, more intrinsic error due to the random gust disturbances. The increase in error may also, in part, be credited to the lag introduced by the operator since he does not respond to each and every gust-induced oscillation and thereby allows error to accumulate more rapidly.

Comparison of performance for the PM and PMH conditions (Figures C1 - C3) shows that introduction of the secondary heading tracking task is accompanied by a decrease in lag, gain, and total system error. The secondary task constitutes a form of task-induced stress in that the requirement to simultaneously monitor and control pitch and heading tracks increases the operator's information processing load. Task-induced stress has been shown to cause regression in operator performance, e.g. in a tracking situation, performance after the introduction of task-induced stress was found by Fuchs (Reference 18) to revert to the level of performing as a simple amplifier. It is hypothesized that the decrease in τ is attributed to a lower capacity to perform analog integration of the pitch signal due to time sharing between pitch and heading dimensions. It is further hypothesized that the decrease in τ results in a decrease in ϵ since the operator now tends to make more frequent corrective movements. It has been generally observed that when an operator is subjected to task-induced stress, he tends to reduce gain in order to avoid excessive error that might otherwise occur (Reference 14), and this is hypothesized to be the case in this instance.

SIDE-STICK CONTROLLER EVALUATION

Introduction

The type of controller used in LAHS flight could be a critical factor in the determination of mission success or failure. The purpose of this evaluation was to provide data for a comparison of the effects of two different types of control stick in simulated LAHS flight: center-stick versus side-stick controller. Accordingly, performance and physiological responses of pilots were studied in the same manner that they were in the main experiment with the use of a side-stick (SSC) instead of a center-stick (CSC) controller.

This section of the report includes a study of the performance and physiological responses made with the SSC, and a comparison of these data with similar data obtained with the CSC.

Method

Subjects. Two pilots who had been subjects in the main experiment were tested with the SSC immediately after the CSC runs were finished. One of these pilots had previously had average error scores, and the other had had smaller than average error scores.

Simulator Development and Controller Configurations. The only change made to the G-seat for the SSC evaluation was the installation of a NASA pencil-type side-stick controller. Technical descriptions of this controller and an arm restraint system that was used are given on page 73 of Appendix D. Diagrams of calibrations of longitudinal and lateral force versus displacement characteristics are presented as Figures D1 and D2, pages 76 and 77.

Figures D3 and D4, pages 78 and 79 illustrate the SSC. The knob of the stick was made of clear plastic, but was taped for these illustrations to provide a better view. Note the pilot's gloves; these were worn for electrical insulation.

Experimental Design. Missions with the SSC were flown in four different conditions, 10L12, 10C12, 20L12, and 20C12. Terrain and gust were varied because they had the greatest effects on performance with the CSC. Each of the two pilots flew a one and one-half hour mission under each of the four conditions, making a total of eight experimental flights with the SSC.

Procedure. Each pilot was given a series of training flights under each of the four experimental conditions before the experiment proper began. The training flights included short periods without turns followed by short periods with turns. Both pilots quickly adapted to the side-arm controller, and, at the end of the training sessions, expressed confidence in their ability to operate with this controller.

The conditions were presented randomly to one pilot. The second pilot flew his missions in an inverted order, i.e. the first flight condition for the first pilot was the last for the second pilot, etc. This was done to control learning. Except for factors associated with the SSC itself, such as size and feel, all conditions and procedures were identical to those that existed with the CSC.

The same kinds of performance and physiological responses that were measured in the CSC flights were measured with the SSC flights. The same score sampling procedure used with the CSC scores was used with the SSC scores so that accurate comparisons between the two sets of scores could be made.

Results and Discussion

Study of Responses Made with the Side-Stick Controller. Average performance and physiological scores for each of the four conditions studied are listed in Table D1, pages 73-75. Averages of comparable CSC scores made by the same two pilots are also included in this table.

Measures obtained from the SSC runs were studied for G effects by comparing means at the different gust levels. Mann-Whitney U-tests were used. No significant differences in either performance or physiological responses were found between the gust levels. It is therefore concluded that G did not produce differential effects among the four SSC conditions.

Terrain effects were studied by comparing C and L measures with U-tests. Significant terrain effects are found on Pe ($p = .001$), He ($p = .001$), Hc ($p = .001$), RMS St ($p = .001$) and St F ($p = .029$). Values of all these measures are greater over contour than over level terrain; Pe is 74 percent greater; He, 41 percent greater; Hc, 97 percent greater; RMS St, 50 percent greater; and St F, 43 percent greater. There are no differences for lag, gain, heart rate, or respiratory rate.

Beginning-end scores were compared so that fatigue effects could be determined. The scores were combined into two groups, contour versus level, for the comparisons since there were no differences due to G in the SSC runs. Significant increases from beginning to end are found in Pe, He, and RMS St. In the case of Pe, errors increased 54 percent in the level flights ($p = .05$), but the increases were not significant in the contour flights. For He, the situation is reversed; errors increase 67 percent in contour flights ($p = .05$), but do not increase significantly in the level flights. The reason for this discrepancy is unclear. In the case of RMS St, the increase is 24 percent ($p = .001$) in contour and 47 percent ($p = .05$) in level flights. There are beginning-end increases in most of the other variables, but these increases are not significant. It is concluded that fatigue affected performance with the SSC. With a larger sample of SSC flights, many of the insignificant increases that occurred in the present study would undoubtedly become significant, and more precise statements about the effects of fatigue could be made.

Turn effects were evaluated by comparing minutes with turns in them to minutes without turns. The only significant turn effects are on RMS altitude error; in flights over contour terrain, there is a 63 percent increase in He during turns, and in flights over level terrain, there is a 46 percent increase. Although these percentages seem great, it should be noted that altitude holding in all SSC flights is very precise; the average RMS per minute He over contour terrain is 18.25 ft., and is only 10.85 ft. over level terrain.

Comparison of Side-Stick and Center-Stick Controllers. Although it would be interesting to study interactions between SSC and CSC scores, it is not feasible to do so with the small number of cases in the samples. The most valid comparisons that can be made on a given variable are those between the two sets of scores, SSC and CSC. Therefore, differences between SSC anc CSC scores on a given variable were studied by comparing the eight means that were available from the 2 flights in the 4 conditions with each type of controller. Results of the *t*-tests that were used to make these comparisons are given in Table D2, page 75. With the exception of heading drift correction (Hc) and frequency of fore and aft stick movements, all SSC-CSC differences are significant, with the SSC scores reduced.

Graphic comparisons of SSC and CSC scores are presented in Figure D5, page 80, for RMS pitch error; in Figure D6, page 81, for RMS altitude error; in Figure D7, page 82, for RMS G; in Figure D8, page 83, for heart rate; and in Figure D9, page 84, for respiratory rate.

Pe and He are both reduced by about 50 percent, a rather dramatic illustration of the increased efficiency of the SSC. RMS G is reduced by about 20 percent, probably due to the quicker and more precise control over the moving seat. An indication of these superior control attributes is seen in the fact that lag is reduced by 41 percent.

Both heart and respiratory rates are reduced in the SSC situation, heart rate by 4.5 percent and respiratory rate by 7.5 percent. These reductions probably stem from the reduced SSC accelerations since both variables increase with G in the CSC situation.

The fact that there is no reduction in St F in the SSC runs is interesting because this variable is closely related to G in the CSC runs; increases in G are associated with increases in frequency of fore and aft movements in the CSC runs. This fact, in conjunction with the finding that there are no differential G effects in the SSC runs, indicates that the arm restraint system used in the SSC runs was effective. Both fact and finding also indicate that arm restraint would be of considerable value in actual LAHS flight with any kind of controller.

The reduced human transfer function (TF) coefficients of lag and gain are probably attributable to different dynamic and mechanical characteristics of both the man and the control stick for the two situations since the computed TF coefficients were for the function of both man and control stick combined. However, the greater lag coefficients for the man-CSC TF may be attributable, in part, to the relatively large force-displacement hysteresis of the CSC. This hysteresis was manifested by a center area 2 inches long where there was no self-centering (see Figure A8, page 45). This meant that the pilot had to provide the centering commands to the stick over approximately the last plus or minus one inch from the stick electrical center located within the small electrical deadband. This center area of no self-centering represented a force feedback deadspace, i.e. within this area the pilot had no force feedback indicative of the distance and direction to the stick's center position. The range of control movements used during the mission was predominantly contained within this force feedback deadspace (one RMS stick displacement was approximately equal to 0.5 inch whereas the force feedback deadspace was • one inch). Thus, within the range of control movement predominantly used, the control stick feedback to the pilot was positional at constant force level rather than force-proportional, i.e. no force gradient "feel" was present for most of the control movements made. The contrary was true for the SSC for which stick displacements were predominantly outside of the force feedback deadspace (one RMS stick displacement was approximately equal to 0.1 inches whereas force feedback deadspace equalled 0.0575 inches aft and zero inches forward).

The facilitative effects of kinesthetic and proprioceptive inputs resulting from control stick feedback are well established. Of particular significance is the immediacy of control stick feedback which provides the operator with more rapid knowledge of his output results than is obtained from the visual feedback channel. A suggested hypothesis is that the more extensive range of force gradient feedback for the SSC enabled the operator to respond more quickly to error signal inputs, i.e. to respond with less lag for the SSC than for the CSC.

As previously noted, the operator may to some degree compensate for system lag effects by increasing his gain. This may account for the higher gain noted for the CSC, i.e. the operator adjusted his gain at a higher level for the CSC due to the greater lag associated with this control stick. Conversely, the greater rapidity and frequency with which SSC movements could be made and the greater accuracy resulting from more immediate feedback of SSC response information resulted in a lower error formation rate than existed for the CSC. It appears intuitively reasonable that the lower the error formation rate the less gain need be applied in order to "catch up with" the error.

GENERAL CONCLUSIONS

When the experimental runs with the CSC are considered, a general conclusion is that pilots of an aircraft like or similar to the TFX should be able to fly successful LAHS missions at 500 feet at constant high speed. However, the degree of success will depend on the nature of the real-world conditions, such as airspeed, terrain, atmospheric turbulence, and flight duration.

The pilot's altitude holding capability should not be affected by airspeed if he is flying in high subsonic or low supersonic regions, and altitude holding should be as efficient over terrain with low hills as over flat terrain. There will, of course, be more aircraft pitching over the hilly terrain.

With a conventional center-stick controller, altitude holding will definitely be affected by the vertical G forces in buffeting conditions. The study showed a steady increase in RMS altitude error from the lowest to the highest RMS G level. The simulated turbulence range was very great, extending from completely calm air to air so turbulent that it is rarely encountered in actual flight. Nevertheless, the rate of error increase as a function of G was constant throughout the range.

Pitch control will also generally be affected by vertical G forces. However, it should not be adversely affected in air normally encountered, within a fairly wide speed range, when the flights are made over level terrain. Over low hilly terrain at a low supersonic speed, G will cause a decrease in efficiency of pitch control from calm to very turbulent air. G will not affect pitch control at a high subsonic speed over low hills within the normal range of atmospheric turbulence, but pitch control at this speed will not be as good in general as it will be at low supersonic speed. Pitch augmentation may, of course, be used to reduce pitching.

From the pilot's standpoint, ninety minute flights should be possible without danger of adverse fatigue effects. However, there are indications that fatigue occurs in flights this long over contour terrain. Although there are no reflections of this fatigue in the performance criterion measures in the study, the point at which aircraft control is affected should be determined where more tasks and/or longer flights are required.

Pitch and altitude errors in the study are markedly reduced with the SSC. In association with these reductions is a reduction in RMS G. The latter reduction decreases physiological stress somewhat, and undoubtedly would decrease aircraft stress as well as increase pilot comfort. There is evidence that at least part of the reduction stems from a decrease in inadvertent control stick inputs due to arm restraint; therefore, arm restraint systems should be investigated for both types of controller. The efficiency of the SSC is generally much greater than the CSC, so it is recommended for use in actual LAHS flight.

The results clearly demonstrate that pilots can physiologically tolerate 1 1/2 hour missions under the G- and task-loadings that were imposed. Heart and respiratory rates were within the normal range, and the biochemical tests do not reveal organ damage. Nevertheless, significant psychophysiological correlations were found. (Heart rate was significantly correlated with both Pe (+.60) and He (+.53), and with G (+.56); while respiratory rate was significantly correlated with G (+.73) and He (+.69). As previously discussed, the correlations may reflect internal changes that affect task performance through modification of physiological responsiveness. This raises one of the most important questions in mission simulation; namely, how to duplicate flight conditions within the pilots as well as for the aircraft. The observed indications of mild but consistent variations in internal processes with flight conditions, coupled with the fact that LAHS missions are dangerous and anxiety-provoking, demonstrate a need for study in which anxiety is induced and varied. Drugs, hormones, or hypnotic suggestion could possibly serve as agents of induction. The indications of boredom at the lowest G levels in the CSC runs emphasize this need because boredom will not be a factor in LAHS missions.

20 March 1964
North American Aviation, Inc.
Columbus, Ohio

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APPENDIX A

EXPERIMENTAL PROCEDURE

G-Seat Frequency Response. The G-seat incorporates a compensator and "G" limiter in cascade with a high pass filter $\frac{2s}{2s+1}$. The compensated frequency response has been calibrated and is presented in Figure A3, page 40 It can be seen from Figure A3 that the frequency response is approximately 4 DB low in the frequency range of 1 to 10 cps and decays rapidly at either higher or lower frequencies. The low frequency decay is due to the high pass filter which prevents the seat from reaching the stops for low frequency inputs where the seat displacement would be large.

The high pass filter in cascade with the compensator and "G" limiter provides for smooth seat return to center upon reaching the seat limits without introducing unsatisfactory dynamics; however, this arrangement somewhat reduces the maximum obtainable "G" for a step or low frequency input. For example, when the pilot commands a large step input the seat responds rapidly and then washes out due to the G-limiter and high pass filter. This washout effect is only apparent for large commands. It would only apply to approximately 10 percent of the total pilot inputs and would have no effect on the higher frequency gust input.

Longitudinal Characteristics. The longitudinal short period characteristics indicated by the derivatives are presented here:

Parameter	M = .9	M = 1.2
$f_N \sim$ cyc/sec	.69	1.05
ζ	.291	.262

The longitudinal short period characteristics in terms of pilot acceptance boundaries are presented in Figure A7, page 44.

It can be seen from Figure A7 that the longitudinal characteristics of the basic airplane (unaugmented) are only marginally satisfactory at Mach Number 1.2 and are satisfactory at Mach Number 0.9. (However, at least one pilot considered the control characteristics satisfactory. See page 87, Appendix E, Pilot's Comments). Note that at Mach Number 0.9 the point on the curve is just above the PIO limit for 5 lbs/g stick force. The calculated force per g for the control system mechanized was 1.9 lbs/g which would indicate that PIO tendencies could be expected at Mach Number 0.9. However, due to the high friction forces in the stick, the actual force required for any deflection up to one inch (2 g's) was on the order of 4 lbs. This would still indicate marginal control force per g at Mach number 0.9 with a probability of PIO tendencies; however, none were apparent during the experiment.

Lateral-Directional Characteristics. The lateral-directional characteristics indicated by the derivatives are also presented here:

Parameter	M = .9	M = 1.2
$f_d \sim$ cyc/sec	.51	.68
h_d	.100	.105
ω_ϕ/ω_d	1.27	1.22

The lateral-directional characteristics in terms of pilot acceptance boundaries are presented in Figure A10, page 47, and are seen to be unsatisfactory at both Mach numbers. This was apparent during the experiment.

Control Stick Forces. The center stick was a standard type with a curved shaft and offset grip as can be seen in Figure A6, page 43. It included an emergency shut-off switch and trim button. It was functional in both longitudinal and lateral modes. The longitudinal control forces can be described in general as having a 4 lbs. per inch spring rate with 4 lbs. of static friction and 3-1/2 lbs. of dynamic friction. These conditions were exactly true for the initial portions of the experiment; however, approximately midway in the experiment the friction forces had increased to over 5 lbs. and it was necessary to rework the servo seals and reduce the friction level. The longitudinal and lateral stick force versus displacement calibrations are presented in Figures A8 and A9, page 45 and 46. The longitudinal force displacement calibration shows two curves representing the initial calibration at the beginning of the experiment and the calibration after the servos were reworked to reduce the friction forces. The two curves are practically identical.

The longitudinal control stick to aircraft relationshipsof control force and displacement per unit of normal acceleration are as follows:

$$\frac{F_s}{\Delta N_L} = 1.9\#/g$$

$$\frac{\delta s}{\Delta N_L} = 0.5 \text{ in}/g$$

The above stick force per unit acceleration is merely academic for small stick displacements in that in order to make a one g command input or a 0.5 in. stick displacement, 4 lbs. of force would be required to overcome the friction forces. The lateral control gain was such to give .02 radians of aileron deflection for one inch of stick deflection.

The majority of the pilot longitudinal control inputs during this experiment were within the friction band so that the forces due to spring rate were masked entirely by the friction forces which were the primary forces the pilot had to contend with.

Physiological Sensors. All electrodes were 7/8" diameter wire mesh electrodes, which were held in place on the body by 1/32" thick patches of adhesive-backed cork. Two patches were used for each electrode: an inner patch which was a hollowed circle of 11/16" inner and 1 1/4" outer diameter. A solid patch 2 inches in diameter was placed over the inner patch. Electrical contact between skin and electrode was facilitated by the use of electrode paste.

The ear transducer consisted of a micro-miniature light bulb imbedded in plastic opposite a miniature photocell similarly mounted. Variations in tissue opacity resulted in variations in the electrical output of the photocell. The unit was placed on the upper lobe of the pinna of the left ear, and held fast at that location by a screw tipped with a 3/8" disk of plastic, thus making the device fasten to the ear like an earring. A hole was cut in the side of the flight helmet so that the helmet could be worn with the earpiece fastened in place.

The impedance pneumograph was a Spacelab Model 130, powered with four 1.5 volt dry cells. The strain gauge for the pneumotachometer was contained in an oxygen mask worn throughout the flights.

To prevent stray electrical currents from interferring with signals from the physiological sensors, pilots were insulated from the seat and its parts. They were required to wear flight suits, boots, and gloves, while parts of the seat usually touched, e.g. control stick and throttle, were wrapped with insulating tape.

<u>Gust Sensitivity</u>. The airplane's gust sensitivity for each configuration tested was estimated by the method outlined in Reference 28.

Config.	M = .9	M = 1.2
	RMS N_L/RMS Wg Est.	RMS N_L/RMS Wg Est.
Basic	.0159	.0164
Pitch Aug 3.5 x M_q 2.0 x M_α	.0136	.0168
Pitch Aug 2.21 x M_q 1.74 x M_α	.0101	.0150

The maximum estimated RMS load factor due to gust would be:

M = 1.2, Basic Configuration RMS Wg = 20 FPS

RMS N_L = 20 (.0164) = .328 g

Recordings were made of the actual RMS gust input to the seat and the seat RMS load factor for each condition of gust level and mach number. The recordings were made with the control stick fixed and a 180 lb. dead weight in the seat over a 25 minute time period for each condition. The results of these check runs indicate that the actual gust RMS input is approximately 12 percent lower than calculated and is due to the initial calibration of gust tapes being somewhat low.

The tabulated results of the check runs are as follows:

Condition	RMS Wg_{Actual}	RMS $N_{L Seat}$ Actual	$\frac{RMS\ N_L}{RMS\ W_g}$ Actual
M=1.2, RMS Wg = 2_{Calc}	1.752	.0181	.0103
M=1.2, RMS Wg = 10_{Calc}	8.36	.1398	.0167
M=1.2, RMS Wg = 20_{Calc}	17.96	.2945	.01642
M= .9, RMS Wg = 2_{Calc}	1.781	.0168	.00945
M= .9, RMS Wg = 10_{Calc}	8.37	.1269	.01516
M= .9, RMS Wg = 20_{Calc}	17.51	.2468	.01411

It can be seen that a very close correlation of estimated to actual gust sensitivity of the aircraft exists for the higher gust levels cases; however, the lower gust level cases indicate a lower sensitivity than estimated. This decay of sensitivity at the very low gust level is due to decay in seat response to the low amplitude displacements. The maximum measured rate of normal load onset due to gust was 40 g's/sec from the computer and 24 g's/sec at the seat.

Gust Characteristics. Gusts were inserted into the problem as a change in vertical velocity, Wg. The gust time history for this experiment was the same as the M=0.9 input used in Reference 1. It was recorded on magnetic tape and was identical for each case. The change in RMS level of the gust was achieved by changing the gain of the taped input. The gust time history was obtained by filtering the output of a white noise generator with $\frac{K}{\tau s + 1}$, where K is a scaling factor between the noise generator and the gust input scaling and τ is a constant inversely proportional to Mach number. Thus, for a given Mach number the filter assumes a fixed function. The distribution of the gust levels was randomized according to a random number table and sampled at a rate which varied inversely with Mach number, the nominal rate being 6 sec per sample at .9 Mach number.

TABLE A1

EQUATIONS MECHANIZED ON THE ANALOG COMPUTER

The five degree of freedom equations of motion along with the Euler equations and scoring equations (RMS) are as follows:

$$\dot{\alpha} = q + Z_\alpha \alpha + Z_\alpha \frac{w_g}{V_0} + Z_{\delta e} \delta e$$

$$\dot{q} = M_\alpha \alpha + M_q q + M_\alpha \frac{w_g}{V_0} + M_{\delta e} \delta e$$

$$\dot{\beta} = -r + \frac{g}{V_0} \phi + Y_\beta \beta$$

$$\dot{P} = L_\beta \beta + L_p P + L_{\delta_A} \delta_A$$

$$\dot{r} = N_r r + N_\beta \beta + N_{\delta_A} \delta_A$$

$$\dot{\phi} = P + \theta \dot{\psi}, \quad \dot{\theta} = q \cos \phi - r \sin \phi, \quad \dot{\psi} = r \cos \phi + q \sin \phi$$

$$\dot{h} = V_0 (\theta - \alpha)$$

$$\Delta N_{L_{pilot}} = \frac{V_0}{g} (\dot{\alpha} - q) + \frac{l_p \dot{q}}{g}$$

$$RMS_{f(t)} = \sqrt{\frac{1}{T} \int_0^T [f(t)]^2 dt}$$

$$P_e = (\theta - \theta_{T+.5})$$

$$H_e = (h - h_T)$$

$$CRT_{INPUT} = K_1 P_e + K_2 H_e$$

TABLE A2

STABILITY DERIVATIVES USED

Deriv.	M = .9 at S.L.	M = 1.2 at S.L.	Units
Z_α	-.937	-1.25	1/Sec
$Z_{\delta e}$	-.379	- .357	1/Sec
M_α	-17.4	-41.1	$1/Sec^2$
M_q	-1.60	-2.22	1/Sec
$M_{\delta e}$	-38.6	-50.3	$1/Sec^2$
Y_β	-.227	-.302	1/Sec
L_β	-110.33	-199.6	$1/Sec^2$
L_p	-2.88	-3.79	1/Sec
$L_{\delta A}$	+69.94	+86.3	$1/Sec^2$
N_r	-.415	-.604	1/Sec
N_β	+10.17	+18.36	$1/Sec^2$
$N_{\delta A}$	+3.92	+3.77	$1/Sec^2$

TABLE A3

SUMMARY OF FLIGHT CONDITIONS

1. 0.9M, 2 ft/sec, L
2. 0.9M, 10 ft/sec, L
3. 0.9M, 20 ft/sec, L
4. 0.9M, 2 ft/sec, C
5. 0.9M, 10 ft/sec, C
6. 0.9M, 20 ft/sec, C
7. 1.2M, 2 ft/sec, L
8. 1.2M, 10 ft/sec, L
9. 1.2M, 20 ft/sec, L
10. 1.2M, 2 ft/sec, C
11. 1.2M, 10 ft/sec, C
12. 1.2M, 20 ft/sec, C

TABLE A4

RECORDED DATA

1. Normal load factor at pilot's seat
2. RMS load factor at pilot's seat
3. Flight path and terrain profile
4. RMS altitude error
5. Projected pitch error plus altitude error (as presented to CRT)
6. Heading angle
7. RMS pitch error
8. Longitudinal stick displacement
9. RMS longitudinal stick displacement
10. Lateral stick displacement
11. Pilot's Lag (τ)
12. Pilot's gain (K)

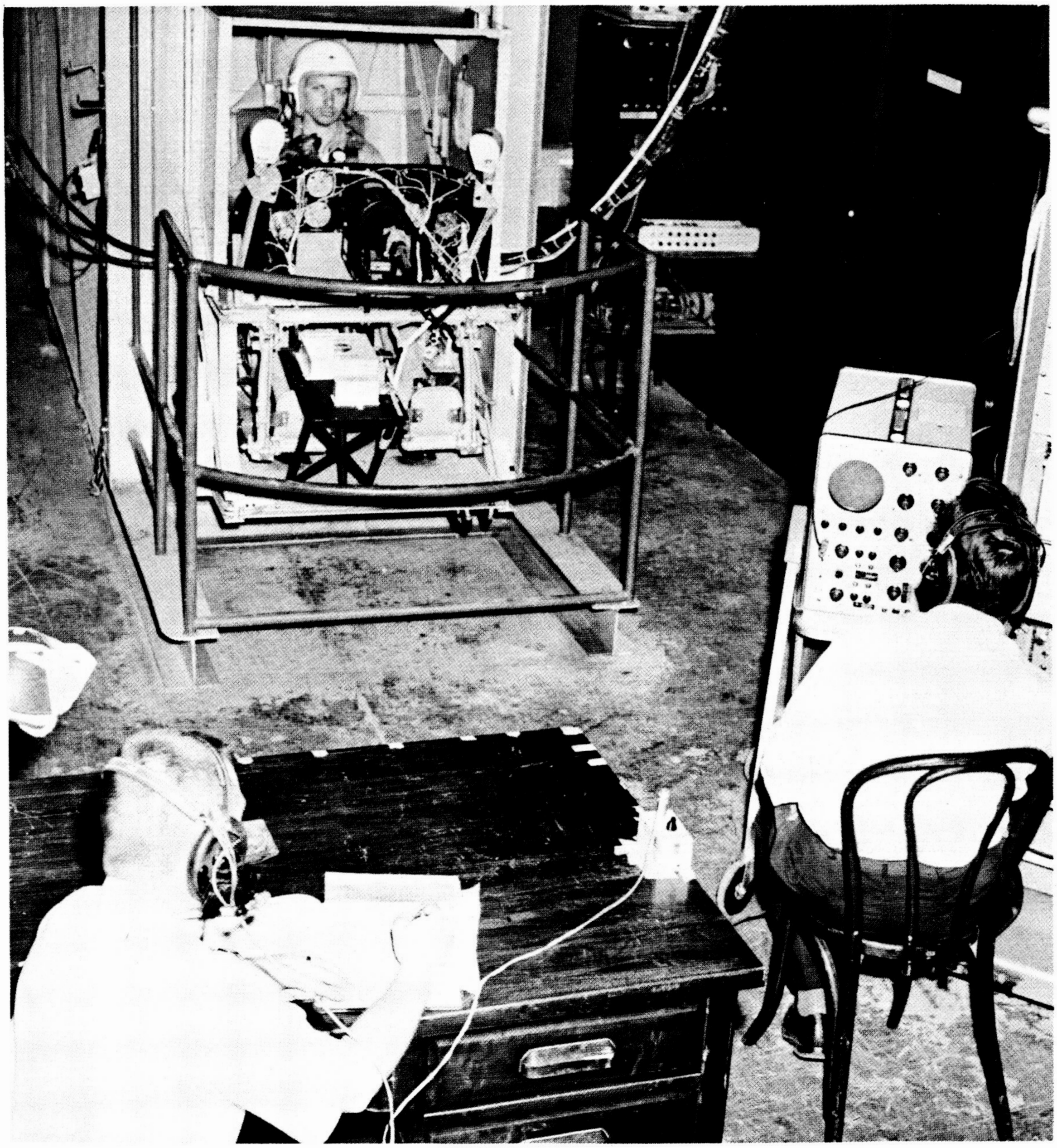


Figure A1
G-seat at lowest point of travel

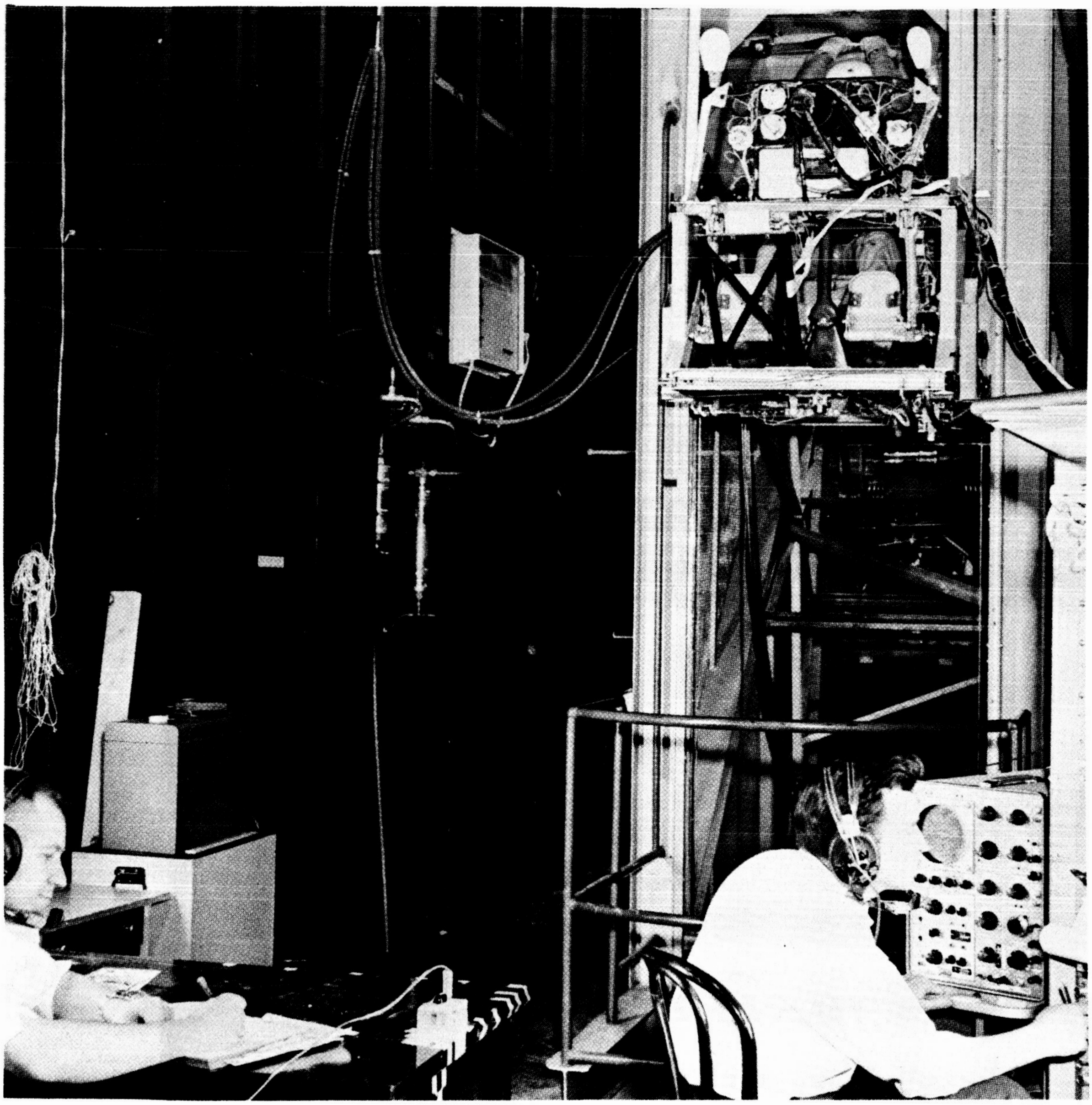


Figure A2
G-seat at midpoint of travel

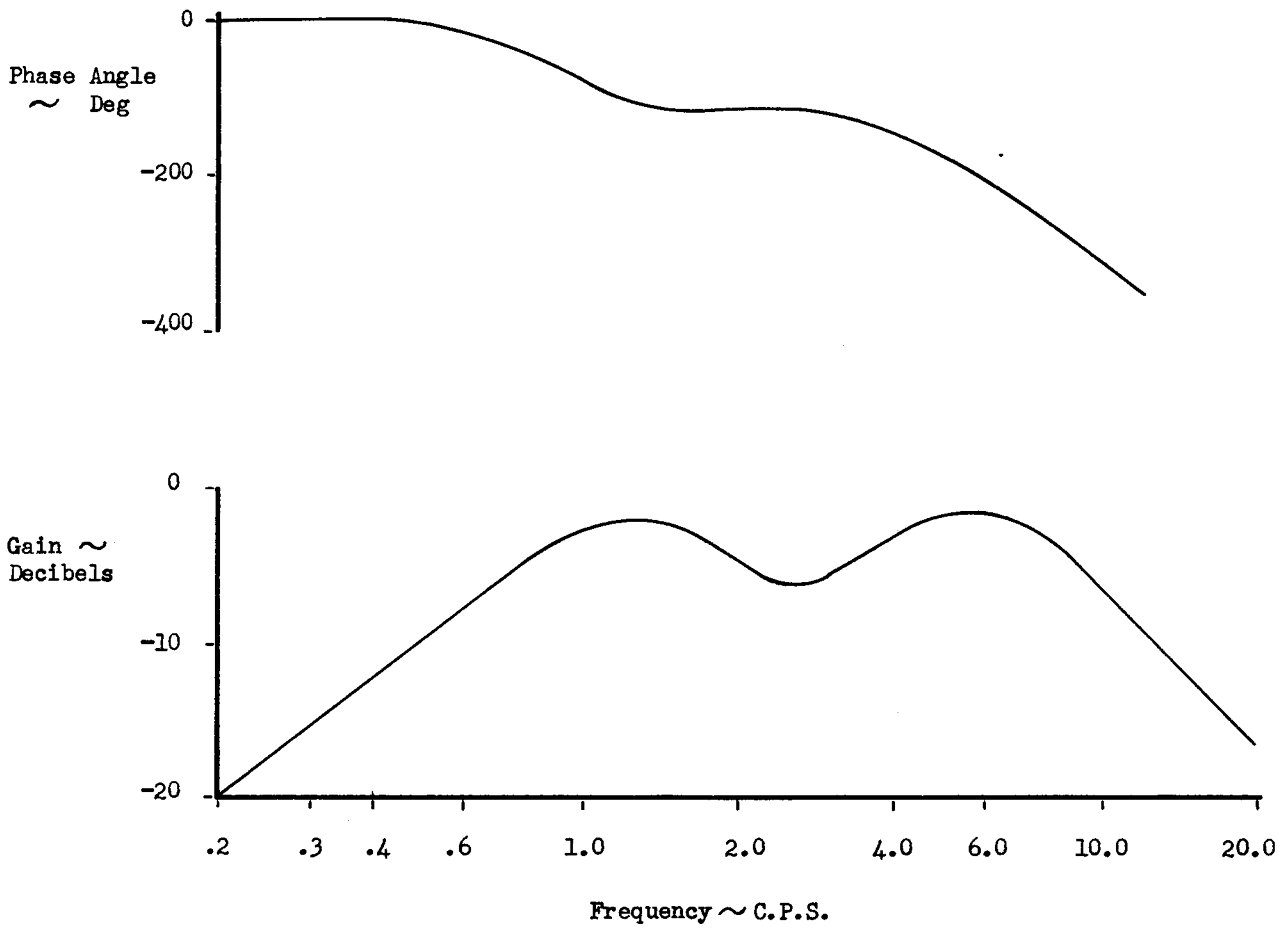


Figure A3

G-Seat Frequency Response Calibration

There was a 180# dead weight in the seat.
There were 0.25 g peak to peak.

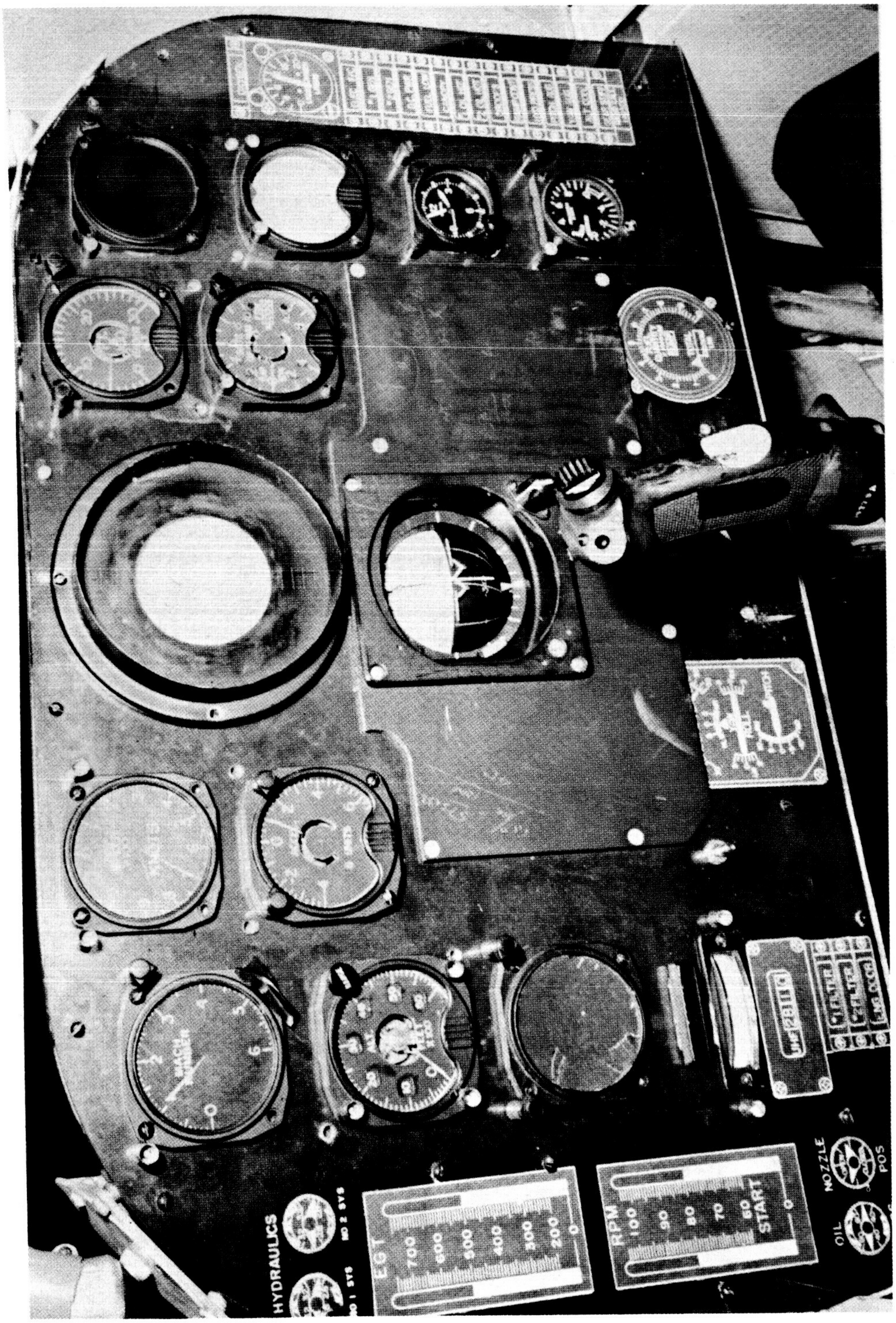
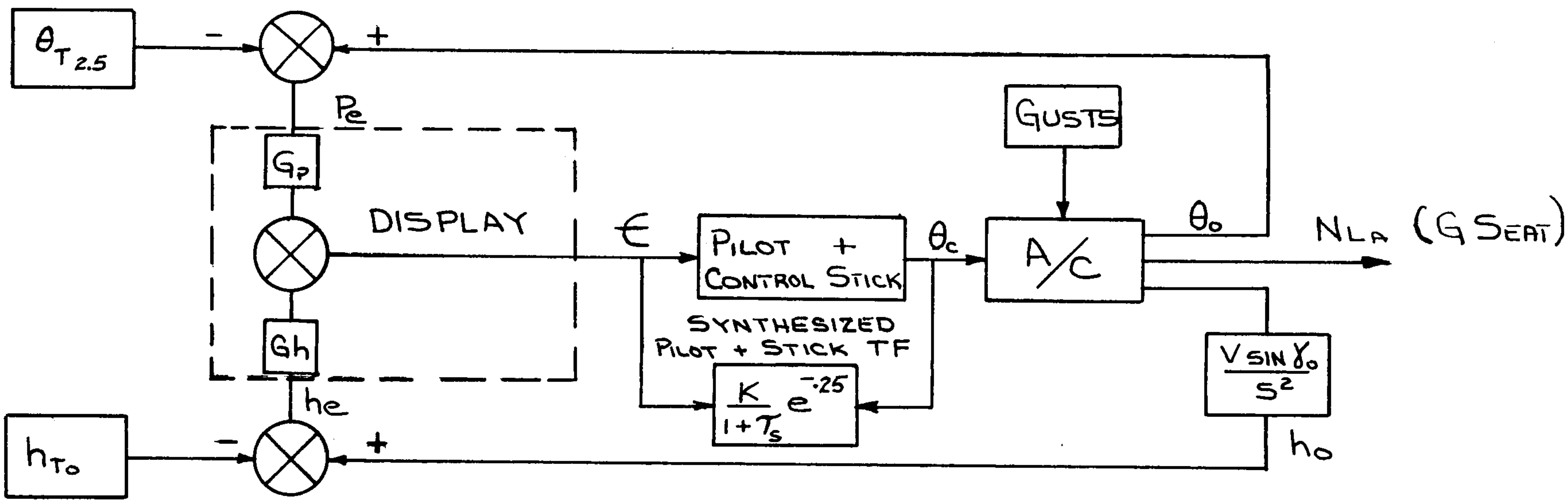


Figure A4

Instrument panel layout



◯ : Summer

$\theta_{T2.5}$: Slope of Terrain in Degrees (2.5 Sec. Lead)

h_{T_o} : Terrain Altitude Plus 500 Feet (Zero Sec. Lead)

Gp: Scope Gain - Pitch Error (Pe) (0.1 inches per degree)

Gh: Scope Gain - Altitude Error (He) (25×10^{-4} inches per foot)

ϵ: Displayed Error

θ_c : Pilot Pitch Command

θ_o : A/C Pitch Response

γ_o : A/C Velocity Vector Angle

V: A/C Velocity

Figure A5
Block Diagram of Signal Flow for Aircraft Altitude and Pitch Control

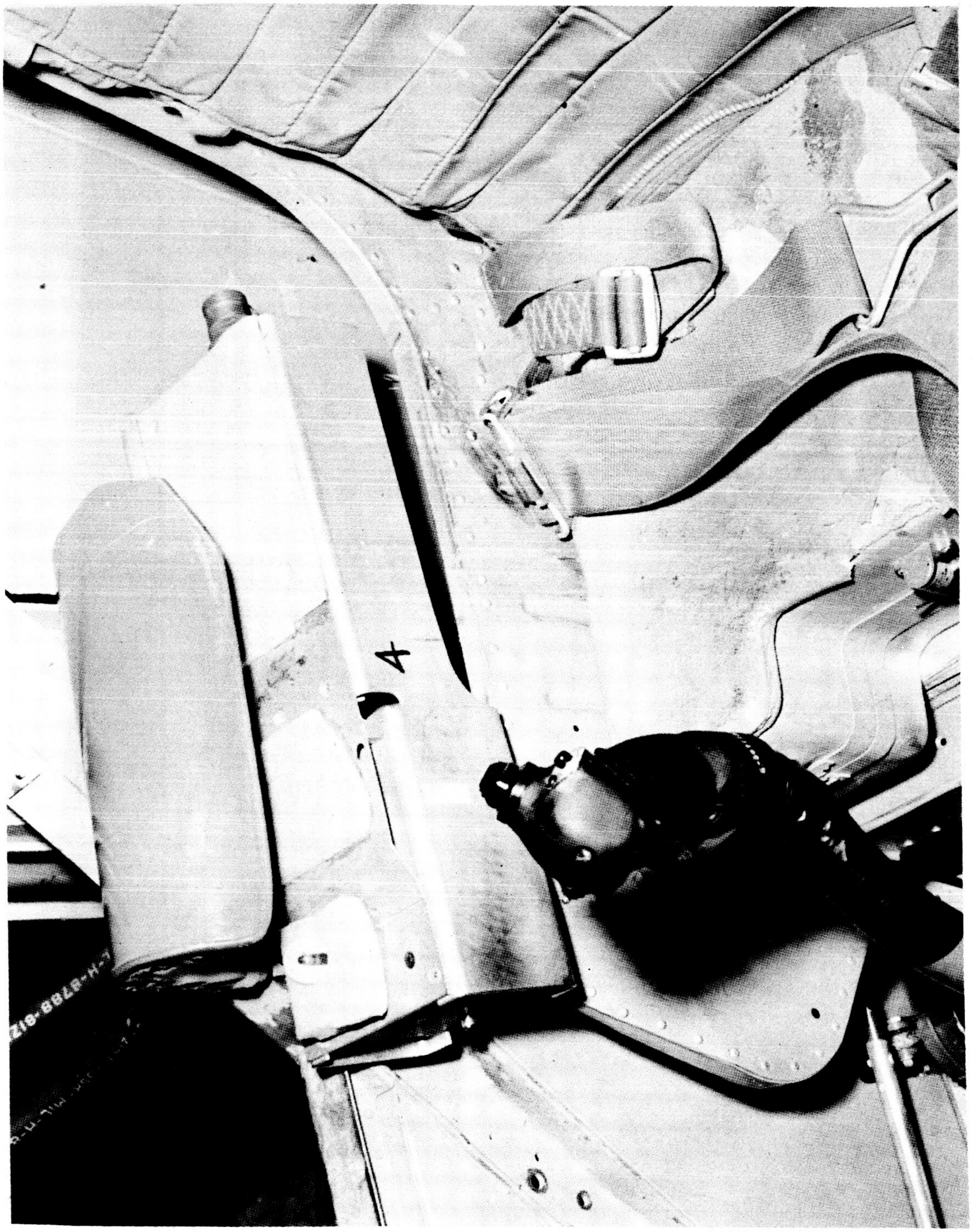


Figure A6
Control Stick

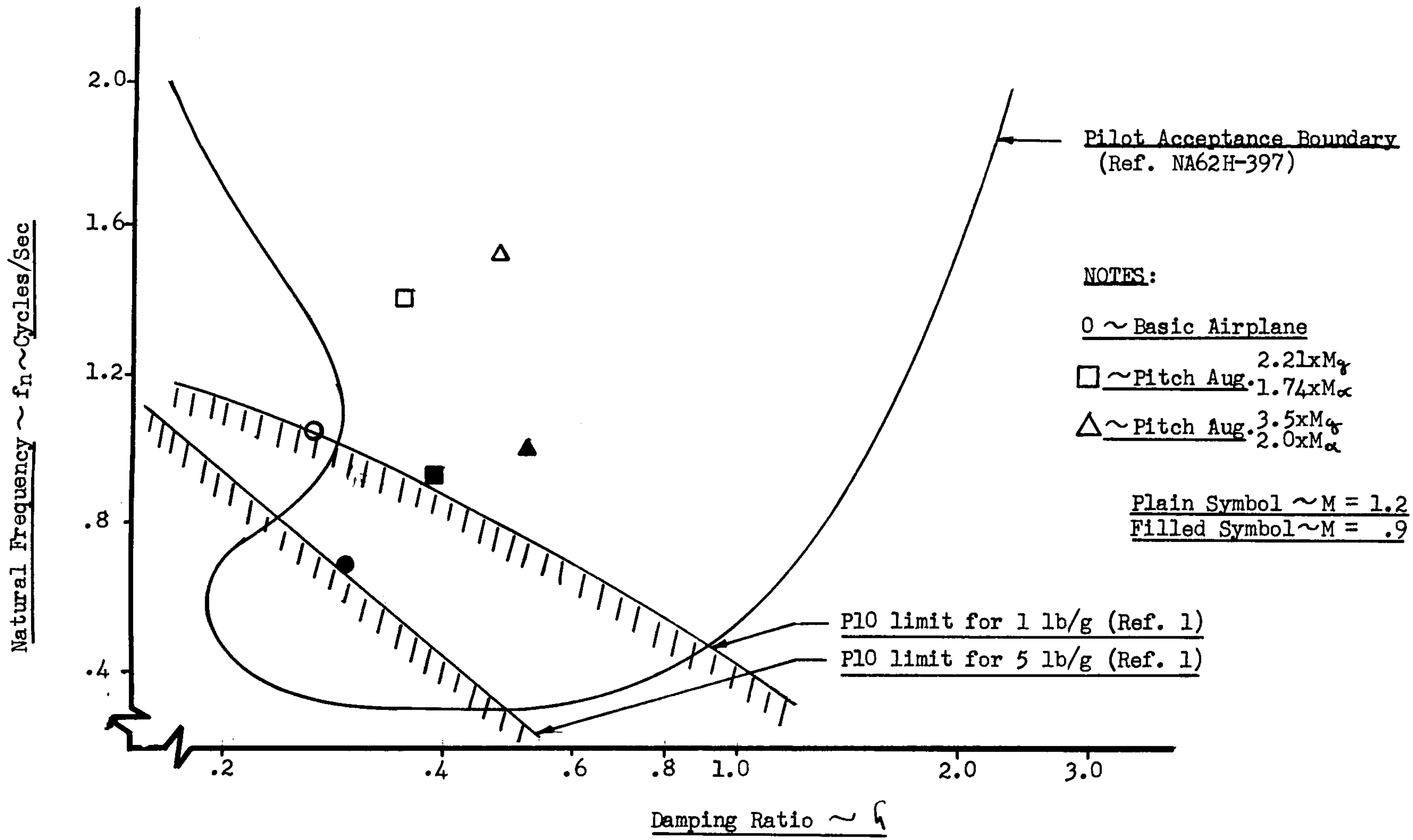


Figure A7

Longitudinal Short Period Stability Characteristics
Center Stick Control

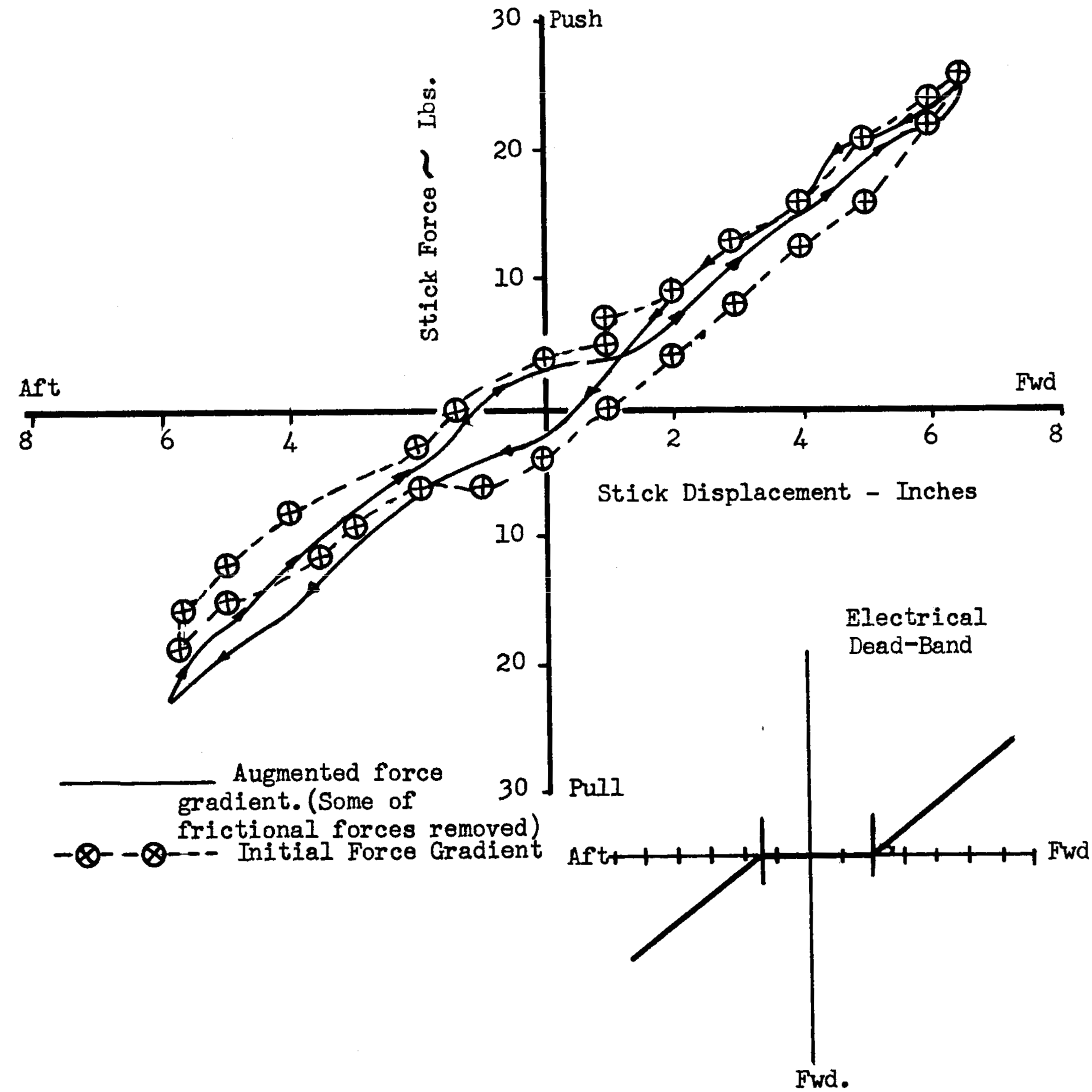


Figure A8
Longitudinal Force-Displacement Characteristics
Center Stick Control

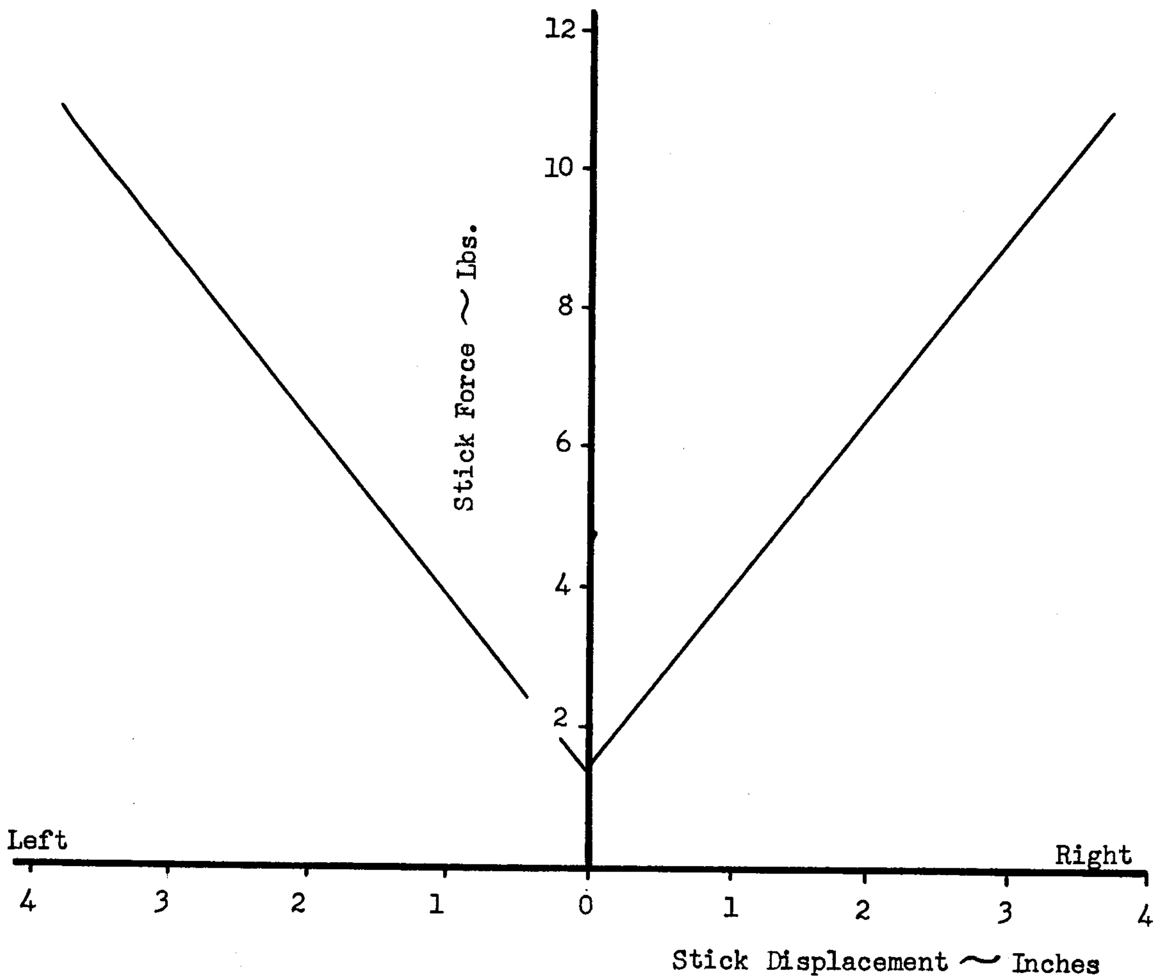


Figure A9
Lateral Force-Displacement Characteristics
Center Stick Control

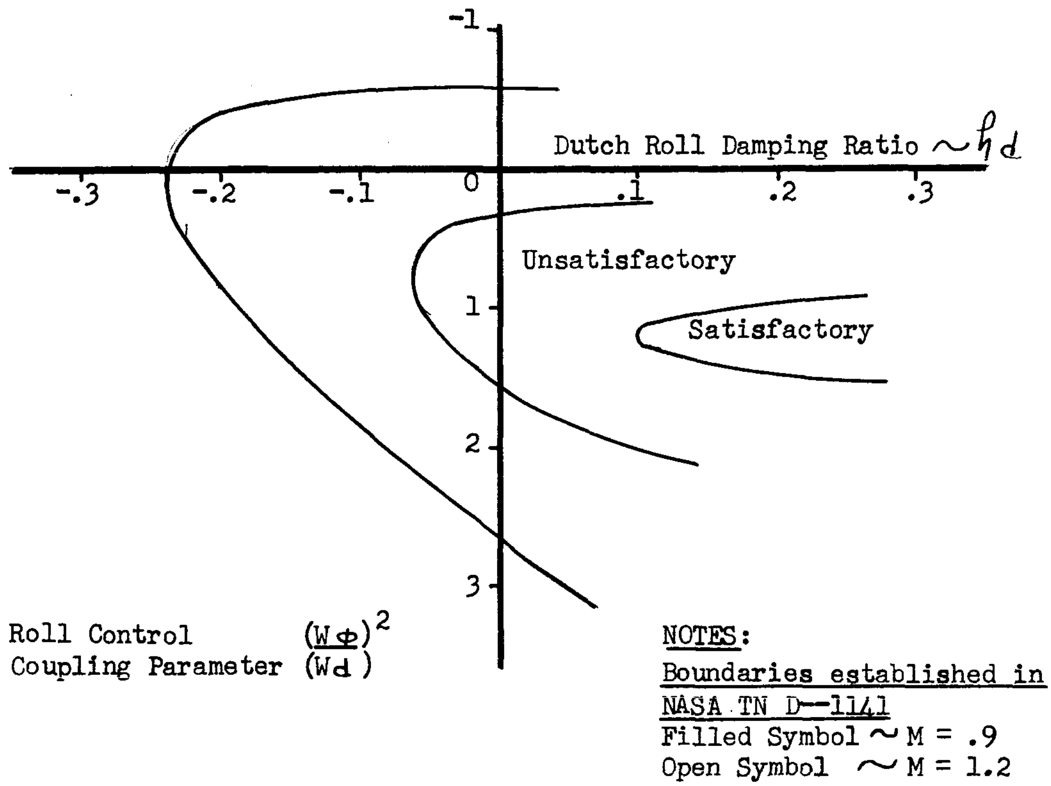


Figure A10
Lateral-Directional Characteristics
Center Stick Control

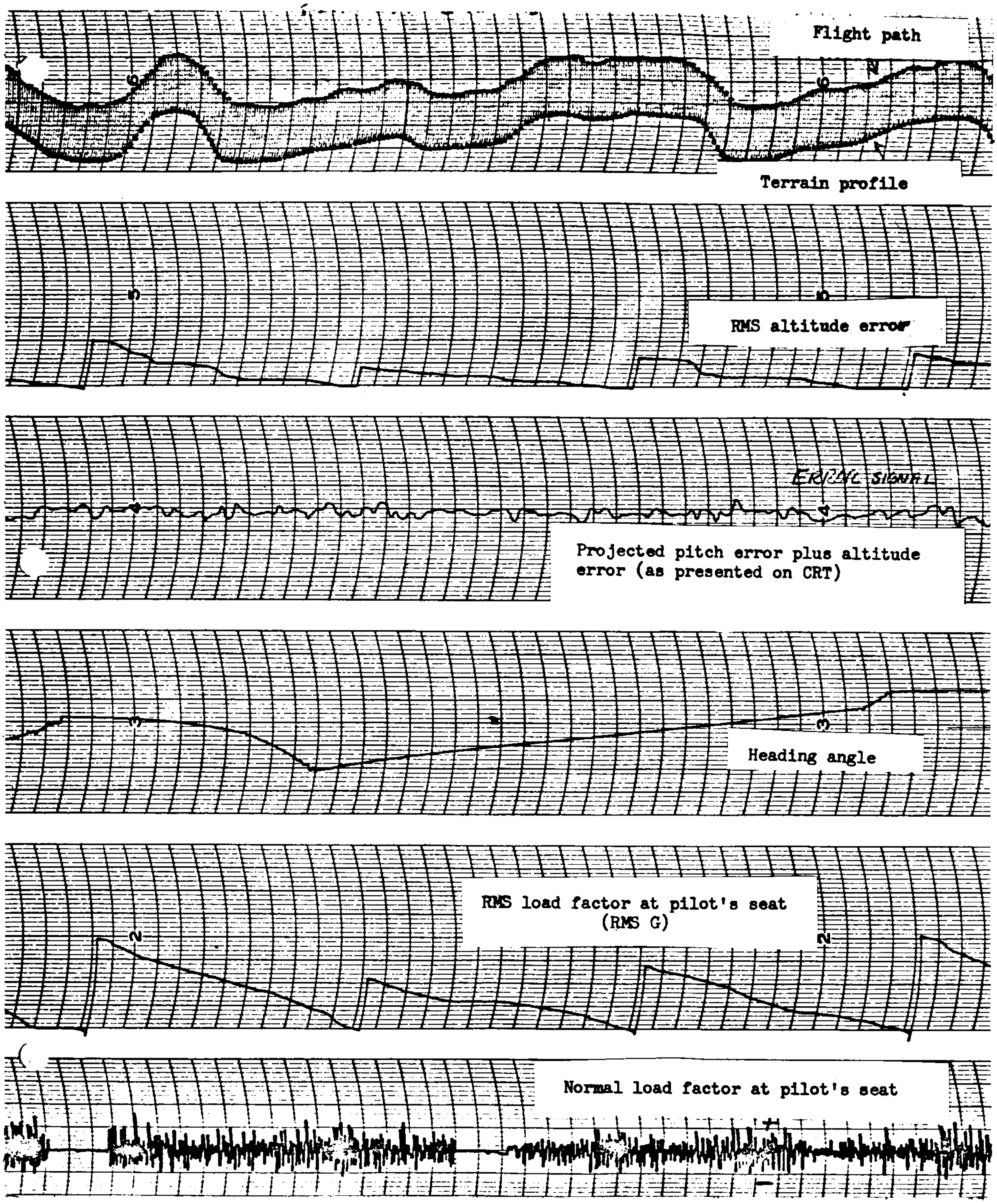


Figure A11
Performance Record I

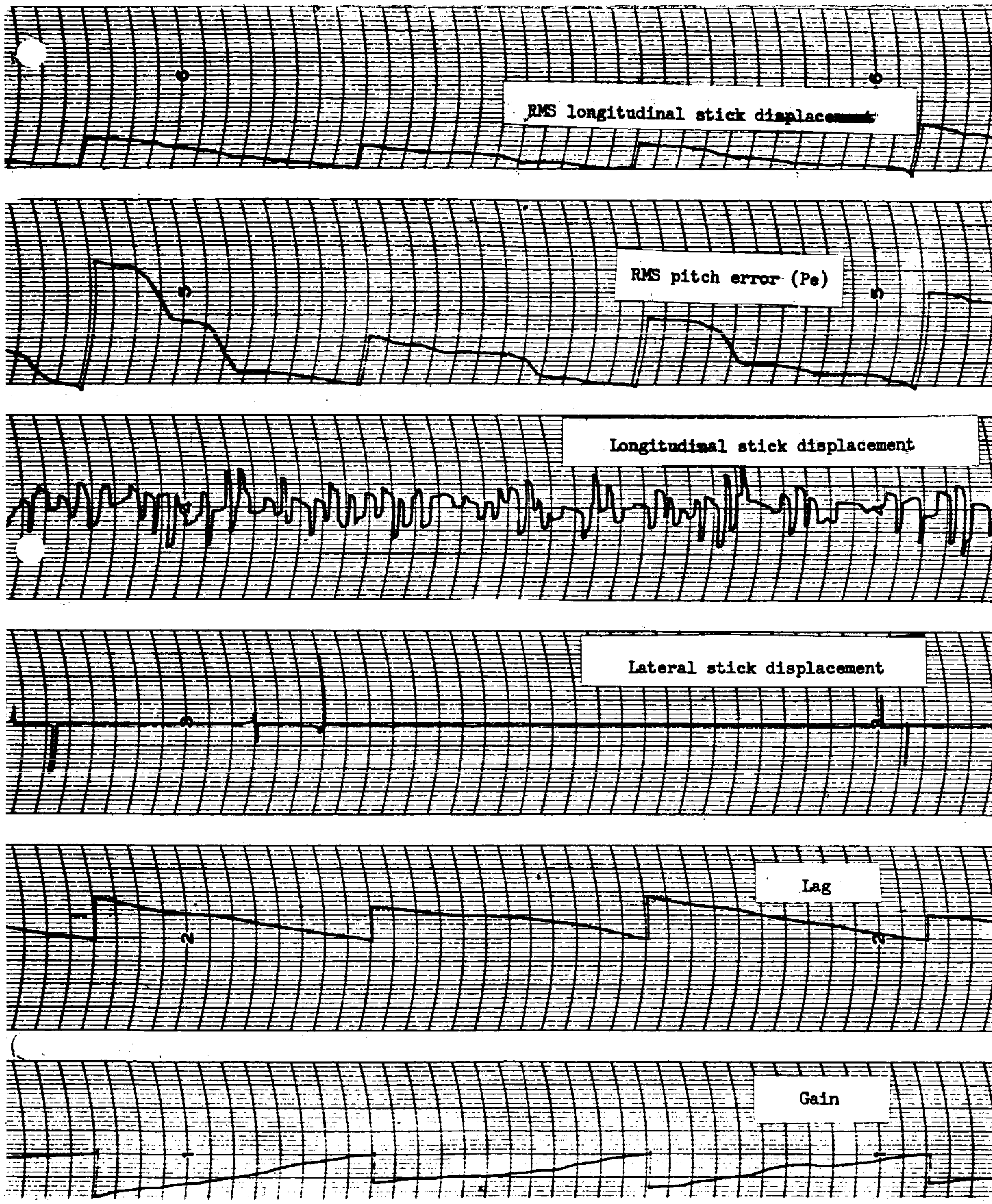


Figure A12
Performance Record II

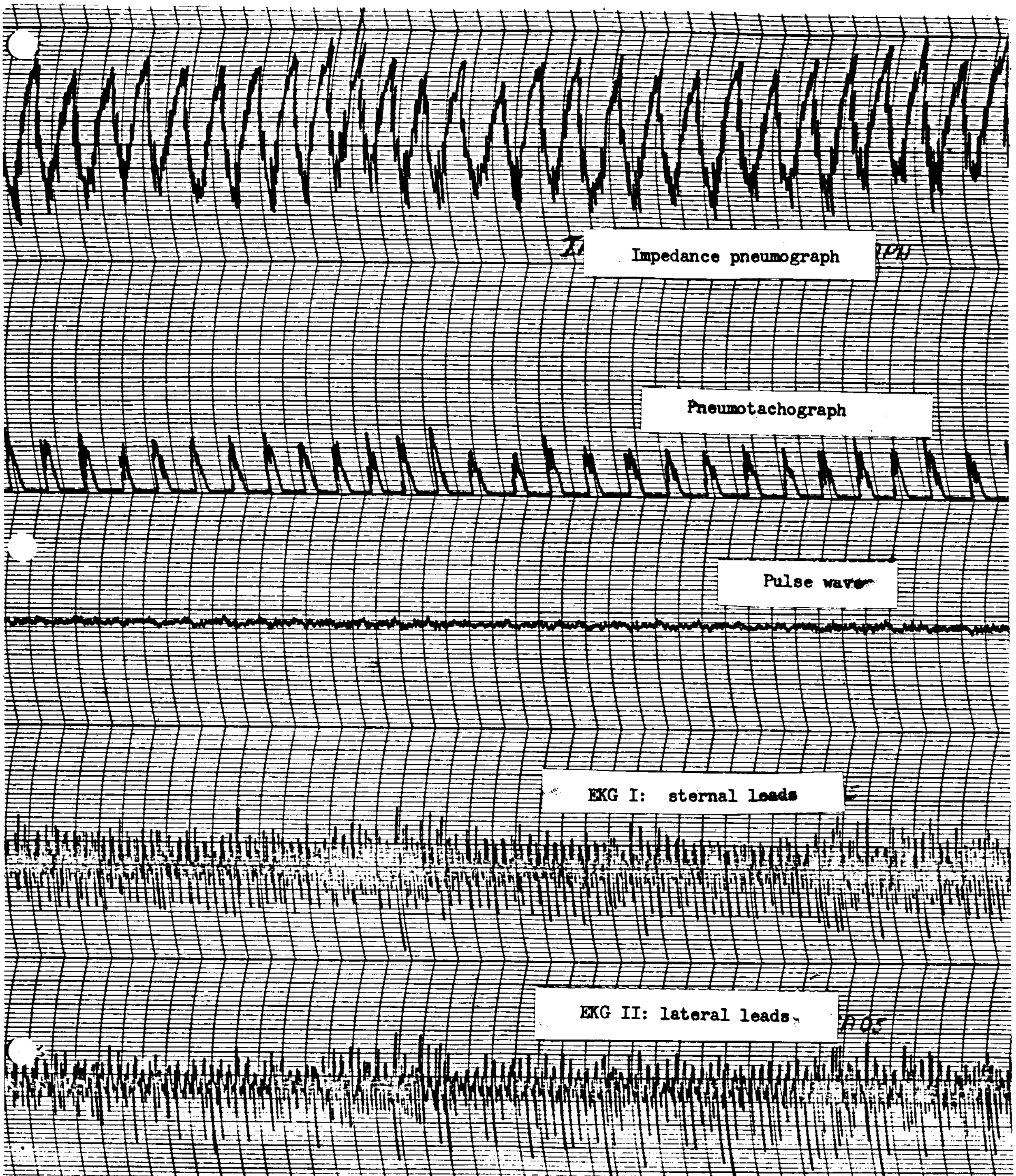


Figure A13
Record of physiological traces

APPENDIX B

EXPERIMENTAL RESULTS: TABLES AND FIGURES

Table B1

Accelerations From Pilot's Seat

Condition	RMS G	Peak G, + and -
2L9	.0288	.45
2C9	.0486	.60
2L12	.0342	.53
2C12	.0666	.60
10L9	.1284	.90
10C9	.1212	.90
10L12	.1512	1.20
10C12	.1518	1.20
20L9	.2304	1.50
20C9	.2420	1.40
20L12	.2736	2.00
20C12	.2910	2.00

Table B2

Actual and Total RMS G

Condition	Actual G	Total G	G Difference
2L9	.0168	.0288	+.0120
2C9	.0168	.0486	+.0318
2L12	.0181	.0342	+.0161
2C12	.0181	.0666	+.0485
10L9	.1269	.1284	+.0015
10C9	.1269	.1212	-.0057
10L12	.1398	.1512	+.0014
10C12	.1398	.1518	+.0018
20L9	.2468	.2304	-.0164
20C9	.2468	.2420	-.0048
20L12	.2945	.2736	-.0209
20C12	.2945	.2910	-.0035

Table B3

RMS Pitch Error Scores, Degrees

Condition	Mean Pe	σ Pe
2L9	.487	.344
2C9	1.828	.573
2L12	.438	.172
2C12	1.407	.458
10L9	.728	.458
10C9	1.839	.573
10L12	.610	.458
10C12	1.576	.573
20L9	1.130	.573
20C9	1.960	.573
20L12	.920	.516
20C12	1.733	.573

Table B4

Summary of Pitch Error Variance

Source	d_f	SS	MS	F	p
Mach Number (M)	1	678.3	678.3	34.9	$<.001$
RMS Gust Level (G)	2	956.4	478.2	24.6	$<.001$
Terrain (T)	1	15,426.4	15,426.4	793.9	$<.001$
M x G	2	99.0	49.5	2.6	-
M x T	1	732.3	732.3	37.7	$<.001$
G x T	2	235.5	117.8	6.1	$<.01$
M x G x T	2	106.8	53.4	2.8	-
W	61	1,185.2	19.4		
Total	72	19,420.0			

Table B5

Feet of RMS Altitude Error

Condition	Mean He	σ He
2L9	23.4	16.8
2C9	23.4	14.0
2L12	23.5	18.0
2C12	19.8	14.4
10L9	28.0	26.6
10C9	23.6	19.8
10L12	28.0	26.2
10C12	35.2	30.0
20L9	35.0	34.8
20C9	33.8	35.2
20L12	33.4	27.4
20C12	35.6	25.8

Table B6

Summary of Altitude Error Variance

Source	df	SS	MS	F	p
Mach Number (M)	1	1.81	1.81	.46	-
Gust (G)	2	36.53	18.26	4.60	$<.05$
Terrain (T)	1	.01	.01	.00	-
M x G	2	4.35	2.18	.55	-
M x T	1	1.94	1.94	.49	-
G x T	2	.74	.37	.09	-
M x G x T	2	2.21	1.10	.28	-
W	59	234.04	3.97		
Total	70	281.63			

Table B7

Heading Errors Per Minute*

Condition	Mean Error
2L9	.298
2C9	.390
2L12	.346
2C12	.353
10L9	.321
10C9	.386
10L12	.328
10C12	.379
20L9	.439
20C9	.320
20L12	.259
20C12	.302

* These errors are given as square inches of heading error per minute, where 1 cm = 2.3° heading error.

Table B8

Summary of Heading Error Variance

Source	df	SS	MS	F	P
Mach (M)	1	2.16	2.16	1.96	-
Gust (G)	2	.65	.32	.29	-
Terrain (T)	1	.65	.65	.59	-
M x G	2	4.17	2.08	1.89	-
M x t	1	.50	.50	.45	-
g x t	2	3.56	1.78	1.62	-
m x g x t	2	3.77	1.88	1.71	-
W	52	57.08	1.10		
Total	63	72.54			

Table B9

Heart and Respiratory Rates

	Flight Date	Airspeed (Mach #1)	G (RMS)	Task	HR* (Ave.)	RR* (Ave.)
Pilot #1	3/6	0.9	.039	L	84	15
	3/6	0.9	.039	C	85	12
	3/5	1.2	.050	C	83	15
	3/5	1.2	.152	C	90	17
Pilot #3	4/9		Orientation		84	20
	4/11	0.9	.039	L	77	20
	4/19	0.9	.039	C	92	18
	4/16	1.2	.050	L	77	16
	4/18	1.2	.050	C	71	15
	4/10	0.9	.125	L	75	20
	4/16	0.9	.125	C	83	17
	4/10	1.2	.152	L	77	20
	4/12	1.2	.125	C	85	18
	4/12	0.9	.236	L	77	20
	4/18	0.9	.236	C	85	20
	4/19	0.9	.236	C	80	18
	4/17	1.2	.282	L	86	20
	4/15	1.2	.282	C	77	20
				ave. L	78	19
				ave. C	82	18
Pilot #4	4/2	0.9	.039	L	78	12
	3/27	0.9	.039	C	81	10
	4/5	1.2	.050	L	75	9
	4/3	1.2	.050	C	83	10
	3/28	0.9	.125	L	77	11
	3/28	0.9	.125	C	85	12
	3/29	1.2	.152	L	83	12
	4/1	1.2	.152	C	76	8

Table B9 (continued)

	4/1	0.9	.236	L	80	14
	4/3	0.9	.236	C	86	18
	4/5	1.2	.282	L	83	13
	4/4	1.2	.282	C	78	12
				ave. L	78	12
				ave. C	82	12
Pilot #5	3/29	0.9	.039	C	86	15
	3/27	1.2	.050	L	91	15
	4/4	1.2	.050	C	79	16
	3/29	0.9	.125	L	79	16
	4/3	0.9	.125	C	88	16
	3/28	1.2	.152	L	80	15
	3/27	1.2	.152	C	88	17
	4/1	0.9	.236	L	86	18
	4/4	0.9	.236	C	80	17
	4/2	1.2	.282	L	82	16
	4/2	1.2	.282	C	86	18
	4/25	1.2	.104	L	84	16
	4/25	1.2	.121	C	91	16
	4/25	1.2	.226	L	86	16
	4/26	1.2	.226	C	81	17
				ave. L	84	16
				ave. C	85	16
Pilot #6	3/18	0.9	.039	L	90	17
	3/21	0.9	.039	C	90	18
	3/20	1.2	.152	L	85	20
	3/19	1.2	.152	C	94	20
	3/15	0.9	.236	L	86	21
	3/15	1.2	.282	L	91	20
	4/23	1.2	.117	L	81	15
	4/22	1.2	.140	C	84	20

Table B9 (concluded)

	4/24	1.2	.236	L	77	16
	4/23	1.2	.227	C	82	19
				ave. L	85	18
				ave. C	87.5	19
Pilot #7	3/19	.9	.039	L	80	14
	3/18	.9	.039	C	86	15
	3/21	.9	.125	L	80	15
	3/18	.9	.125	C	89	
	3/20	1.2	.152	L	76	13
			.152	C		
	3/15	0.9	.236	L	86	15
	3/21	0.9	.236	C	88	19
	3/20	1.2	.286	L	87	15
	3/22	1.2	.286	C	83	18
				ave. L	83	15
				ave. C	86.5	17
Pilot #8	4/24	0.9	.039	L	83	15
	4/17	0.9	.039	L	74	14
	4/11	0.9	.039	C	78	18
	4/24	1.2	.050	L	72	13
	4/23	1.2	.050	C	81	20
	4/10	0.9	.125	L	85	24
	4/25	0.9	.125	C	75	19
	4/12	1.2	.152	L	87	20
	3/8	1.2	.152	C	83	20
	4/16	1.2	.286	L	80	17
	4/11	1.2	.286	C	80	20
				ave.L	80	18
				ave.C	80	20

* Heart rates (HR) and respiratory rates (RR) are given in beats per minute and expirations per minute, respectively.

Table B10

Urinary 17-Ketosteroids and Catecholamine Excretion

Pilot	Date	Total Vol. (ml)	Total Creatinine (mg)	Catecholamine mg/TV	Catecholamine mg/g. creat.	17 Ketosteroid mg/TV	17 Ketosteroid mg/g. creat.
1.	2/23 a	2080	2460	22.3	9.07	25.8	10.5
	3/3 a	1250	1600	15.0	9.38	16.0	10.0
	3/5 b	1325	1940	19.7	10.2	12.6	6.5
2.	2/4 a	1305	1430	17.0	11.9	9.9	6.9
	2/21 b	730	1370	5.4	3.9	10.5	7.7
3.	3/31 a	1875	1680	18.8	11.2	11.1	6.6
	4/14 b	850	1420	15.2	10.7	8.0	5.6
4.	3/19 a	1175	1600	7.4	4.6	8.7	5.4
	3/20 a	1020	1615	8.2	5.1	6.0	3.7
	4/2 b	710	1260	7.1	5.6	6.5	5.2
5.	3/18 a	780	1385	13.9	10.0	9.1	6.6
	4/1 b	1170	1730	12.3	7.1	17.2	9.9
	5/2 b	500	710	5.4	7.6	4.7	6.6
6.	3/5 a	1250	1890	18.1	9.6	17.8	9.4
	3/7 a	1250	1200	11.1	9.3	7.3	6.1
	3/19 b	670	990	5.3	5.4	9.4	9.5
Normal Range	min.	1000	1000	0	6	12	7
	max.		1700	10.3	10	25	15

The letter a indicates that the specimen was obtained before simulated flights began and b after simulated flights had occurred.

Table B11

Serum Cholesterol

Pilot	Date*	Total Cholesterol mg/100 ml	Cholesterol Esters % Total
1.	2/27 a	257	67
	2/28 a	270	71
	3/2 (0830)b	291	65
	3/2 (1930)b	257	63
	3/3 (1130)b	256	67
	3/4 b	283	67
	3/6 b	285	68
	3/8 b	260	70
2.	2/25b	163	68
	2/27b	170	68
	3/1 b	173	73
3.	3/31 a	220	
	4/2 a	240	
	4/4 a	246	
	4/19 b	233	
4.	4/1 a	240	
	4/2 b	250	
5.	3/18 a	233	
	3/20 a	226	
	3/22 a	223	
	4/1 b	244	
	4/2 b	236	
6.	3/4 a	195	
	3/6 a	200	
	3/8 a	182	
	3/11 a	263	73
	4/24 b	226	
7.	3/11 a	259	65
8.	4/10 a	259	65
	4/24 b	335	
	Normal range min.	110	64
	max.	240	76

* The letter a indicates that the specimen was obtained before simulation flights began and b after simulated flights had occurred.

Table B12

Serum Enzyme Activities

Pilot	Date*	GOT	GPT	LDH	MDH	ALK PH	PHI	LAP	ALD
1.	2/25 a	10							
	2/28 a	10							
	3/1							340	
	3/2 b	23	30	300					
	3/2 b	26	15	250					
	3/3 b	33	10	275					
	3/4 b	13	6	200					
	3/6 b								
	3/8 b	36	10	250					
	3/9	36	10	250					
2.	2/25 b	10							
	2/27 b			250					
	3/1 b							260	
3.	3/31 a	16	16	150	200	37		380	230
	4/2 a	26	26	200	200	35		360	190
	4/4 a	19	19	300	150	47		420	190
	4/19 b	19	9	200	250	75		310	175
4.	4/1 a	23	13	250	175	75		350	240
	4/2 b	9	6	295	-	-		430	-
5.	3/18 a	13	13	200	-	-		360	-
	3/20 a	16	16	200	200	70		365	175
	3/22 a	23	6	300	250	83		340	210
	4/1 b	9	6	250	200	75		400	230
	4/2 b	13	13	250	-	-		400	-
6.	3/4 a	9	6	175	200	59		430	200
	3/6 a	16	9	250	200	66		510	190
	3/11 a	7							
	3/8 a	9	9	175	225	60		460	215
	3/22 b	19	0	175	-	-		-	-
	4/24 b	16	6	175	200	50		430	235
7.	3/11 a	16							
	3/22 b	16	0	225					
8.	4/10 a	19	0	175	300	37		420	205
	4/24 b	23	9	175	225	65		370	215
Norman Range	Min.	0	0	150	150		10	100	50
	Max.	40	20	300	300		20	310	150

Table B13

Tests for Pitch Error Fatigue Effects

Condition	t	df	p
2L9	1.86	10	< .05
2C9	2.43	12	< .05
2L19	.42	6	-
2C12	8.82	10	< .0005
10L9	.70	6	-
10C9	3.14	10	< .02
10L12	.002	10	-
10C12	.01	8	-
20L9	1.58	10	-
20C9	1.04	6	-
20L12	.37	8	-
20C12	.22	12	-

Table B14

Tests for Altitude Error Fatigue Effects

Condition	t	df	p
2L9	1.43	10	-
2C9	1.43	10	-
2L12	.11	6	-
2C12	2.81	10	< .01
10L9	4.80	6	< .005
10C9	1.74	10	-
10L12	.24	10	-
10C12	1.44	10	-
20L9	.85	10	-
20C9	.00	6	-
20L12	1.64	8	-
20C12	3.20	12	< .005

Table B15

Tests for Longitudinal Control Stick Displacement Fatigue Effects

Condition	t	df	p	% Increase
2L9	2.286	3	-	-
2C9	7.000	3	<.0005	39
2L12	.300	3	-	-
2C12	2.583	3	<.05	31
10L9	1.588	2	-	-
10C9	4.700	2	<.025	25
10L12	1.136	5	-	-
10C12	3.400	2	<.05	24
20L9	1.200	3	-	-
20C9	1.656	3	-	-
20L12	1.704	4	-	-
20C12	3.411	5	<.05	14

Table B16

Mean Values of Associated Performance Measures

Condition	RMS St	St F	Lag	Gain
2L9	.154	4.0	-	-
2C9	.232	5.6	-	-
2L12	.198	4.6	.490	.254
2C12	.264	7.4	.641	.166
10L9	.202	5.8	.610	.342
10C9	.256	6.7	.568	.296
10L12	.246	6.6	.212	.220
10C12	.324	5.6	.229	.064
20L9	.284	6.9	.446	.304
20C9	.302	5.6	.439	.404
20L12	.328	7.8	.159	.188
20C12	.422	9.0	.221	.266

Table B17

Intercorrelation of Criterion and Associated Measures

	Pe	He	Hc	RMS St	G	St f	Lag
RMS St	.55*	.70*	-.12	-	-	-	-
G	.39	.86**	-.26	.90**	-	-	-
St F	.28	.34	-.06	.66*	.64*	-	-
Lag	.07	-.06	.33	-.03	-.05	.19	-
Gain	.23	.50	-.01	.20	.47	-.04	.38

* p = .05; ** p = .01

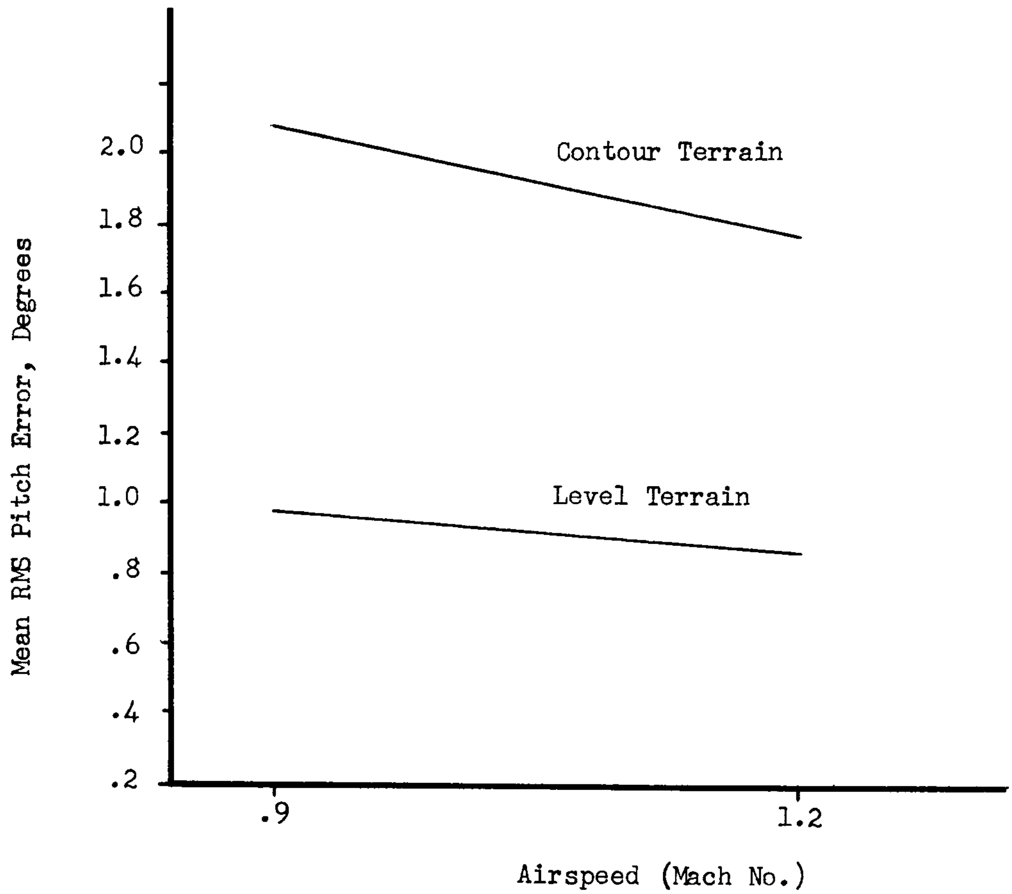


Figure B1
Plot of Means Under Terrain by Airspeed Interaction

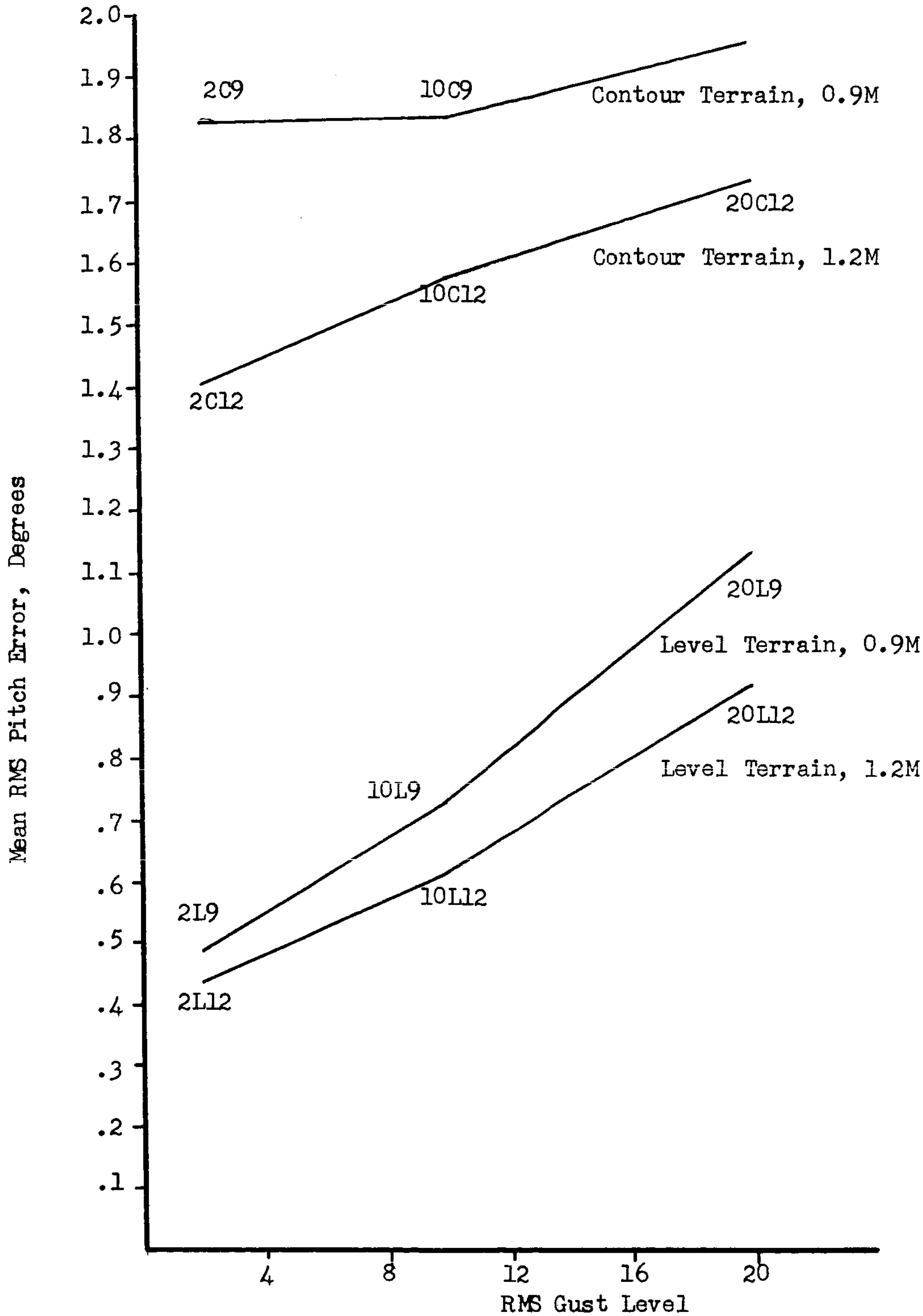


Figure B2
Pitch Error as a Function of Gust

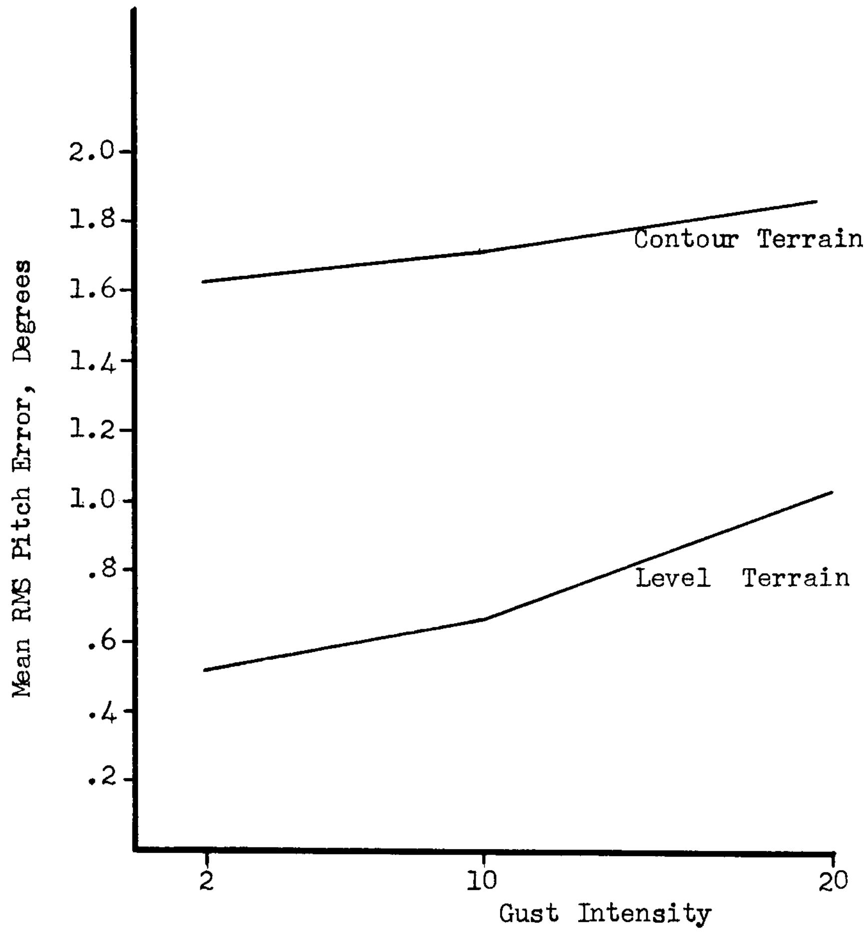


Figure B3
Plot of Means Under Terrain by Gust Conditions

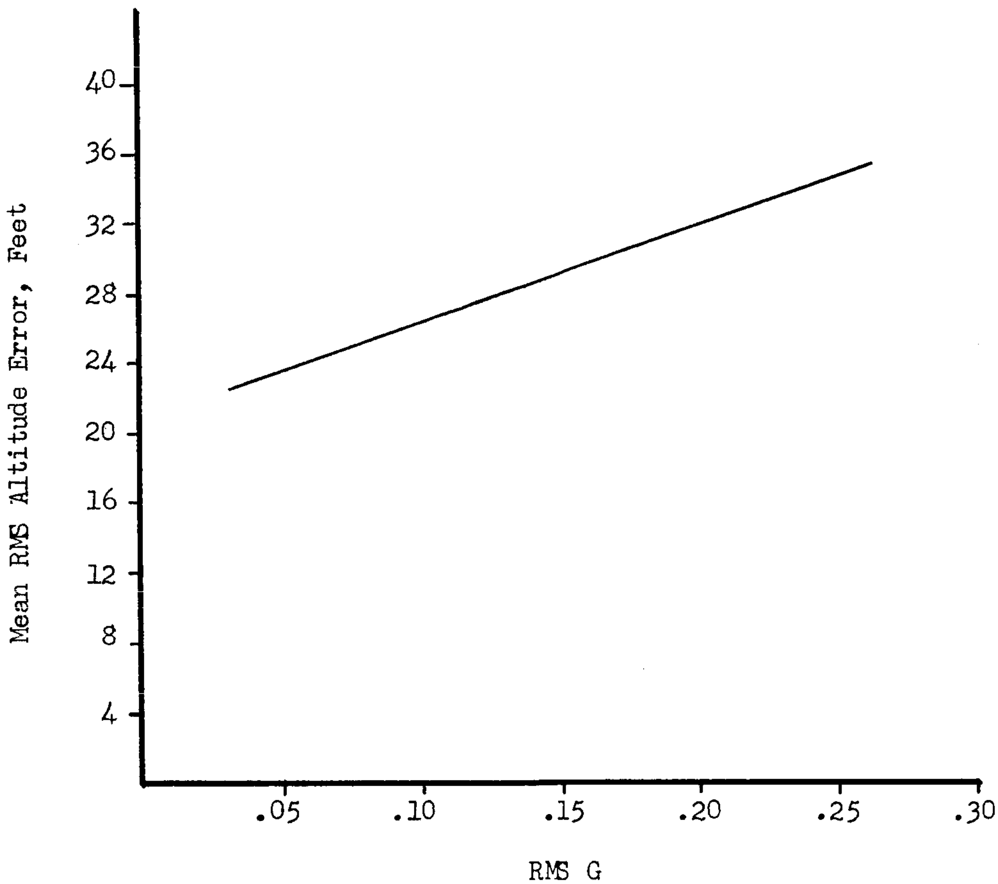


Figure B4
Altitude Error as a Function of G

APPENDIX C

PILOT DYNAMIC RESPONSE

Details of Human Transfer Function Synthesis and Scoring Procedure

The transfer function synthesis technique used is described in Reference 30. Figure A5, page 42, presents a block diagram of the signal flow for aircraft altitude and pitch control. Note that the transfer function synthesized is for the pilot and control stick combined. Also note that θ_o represents the angle between the longitudinal axis of the aircraft and the horizontal plane whereas γ_o represents the angle between the velocity vector and the horizontal plane, i.e.

$$ {}_o = \theta_o - \alpha $$

where α is the aircraft angle of attack.

The error signal (ϵ) displayed on the CRT was a weighted function of the pitch error (P_e) and altitude error (h_e). (One inch of error on the CRT represented 10^o of pitch error or 400 feet of altitude error.) Thus, one radian of P_e yielded the same ϵ displacement as 2286 feet of h_e. A trace of the error signal actually tracked during flight was obtained (see the error signal trace on the same performance record, Figure A12, page 49. The areas under the curves of the trace were measured with a planimeter to provide a measure that was proportional to the total integrated absolute error ($\int |\epsilon| dt$). These measurements are in square inches. They are studied in this form because the displayed error represented a combination of projected pitch error plus altitude error. The units of the pilot gain (K) in the synthesized TF are radians of stick deflection per inch of error on the CRT. The lag coefficient (τ) is expressed in seconds.

The negative values of τ and K that were occasionally obtained are due to an artifact of the coefficient determining circuit. This circuit is tested by substituting an electrical "Manalog" for the man (see Reference 30). Transfer function coefficients of the Manalog are selected to be representative of the man's for the particular tracking condition. The accuracy with which the TF synthesis circuit reproduces the known values of the TF coefficients for the Manalog has been found to be very high for a variety of transfer function values. The TF synthesis circuit has been found, however, to produce artifactual results for positive Manalog coefficients close to zero, viz., it has been found to yield negative values under such circumstances. For this reason, the negative values of τ and K indicated in Figures C1 and C2 are to be considered equivalent to a nominal value of zero. The fact that the coefficients obtained are sometimes negative is an indication of errors of the synthesized values due to uncorrelated noise injected by the operator and the equipment.

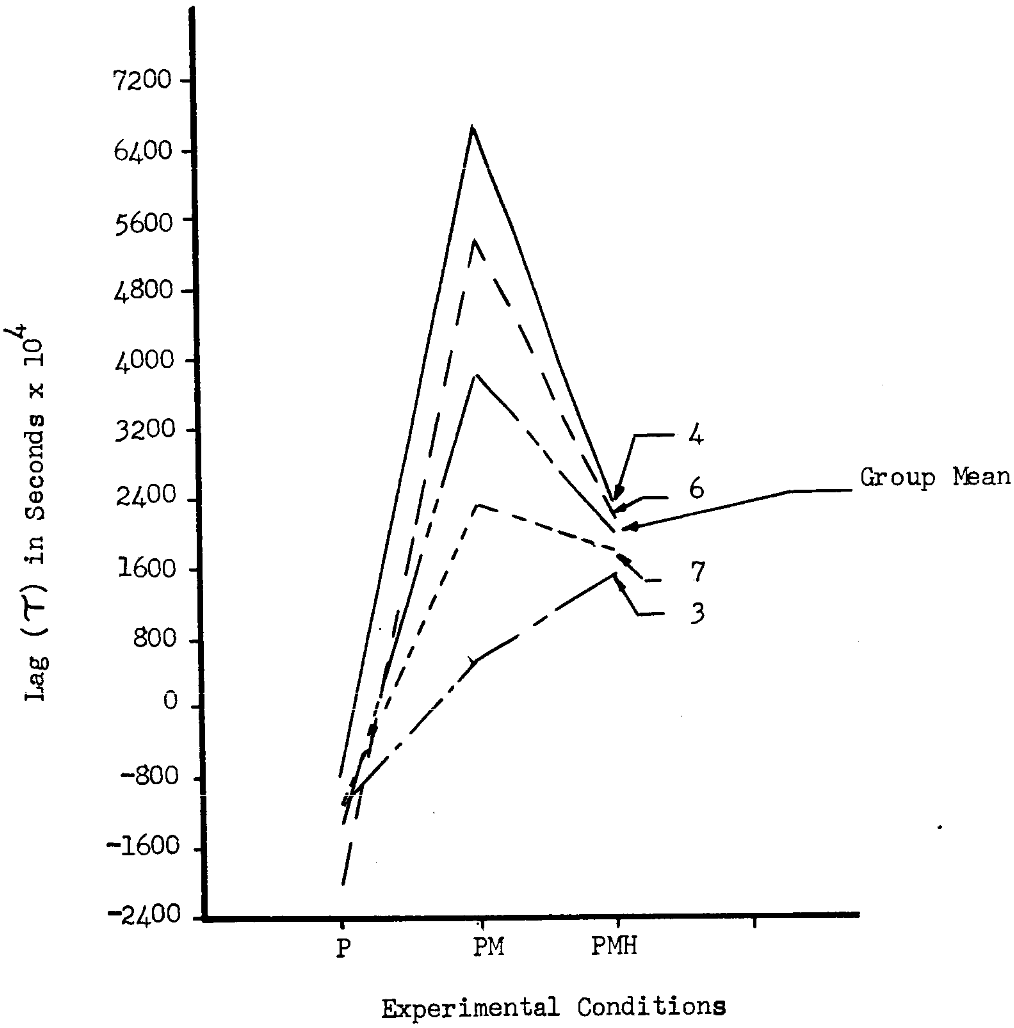


Figure C1
Human Transfer Function Lag Coefficients (τ)

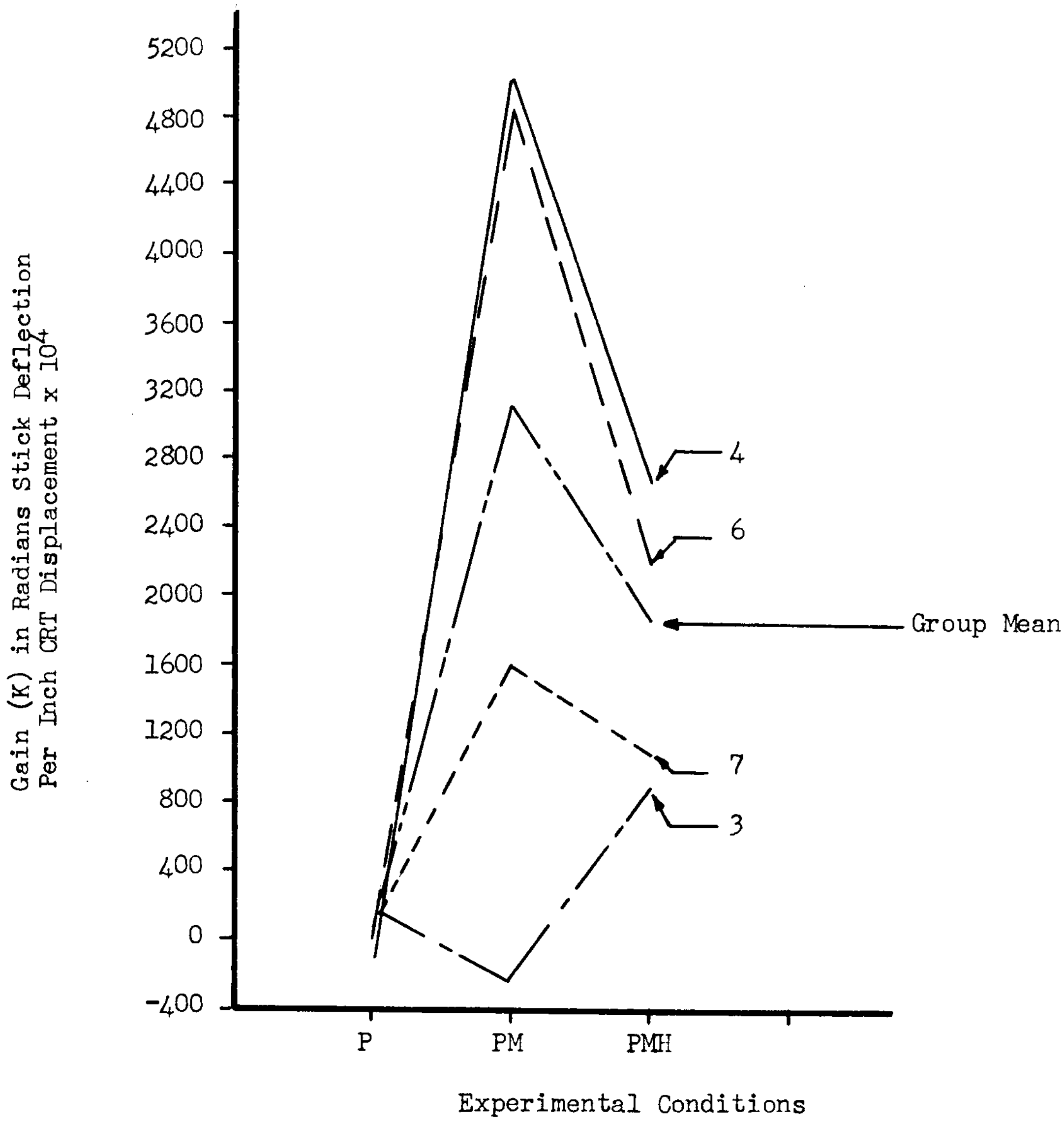


Figure C2
Human Transfer Function Gain Coefficients (K)

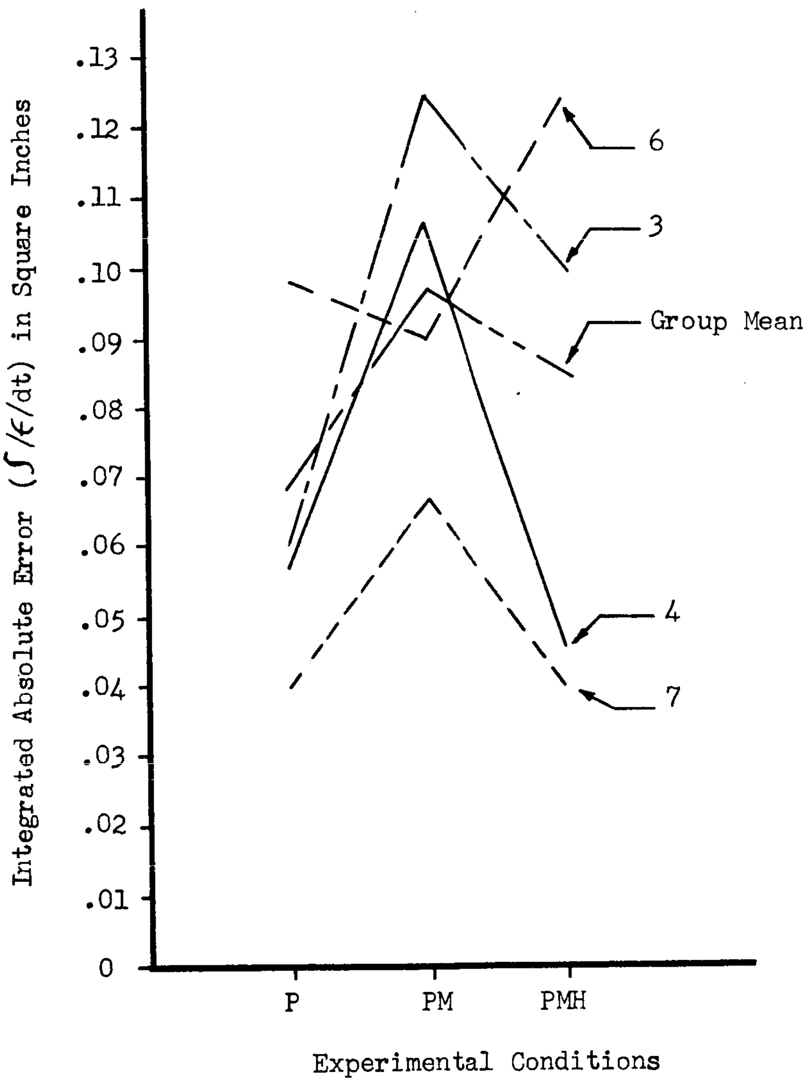


Figure C3
Integrated Absolute Error Scores

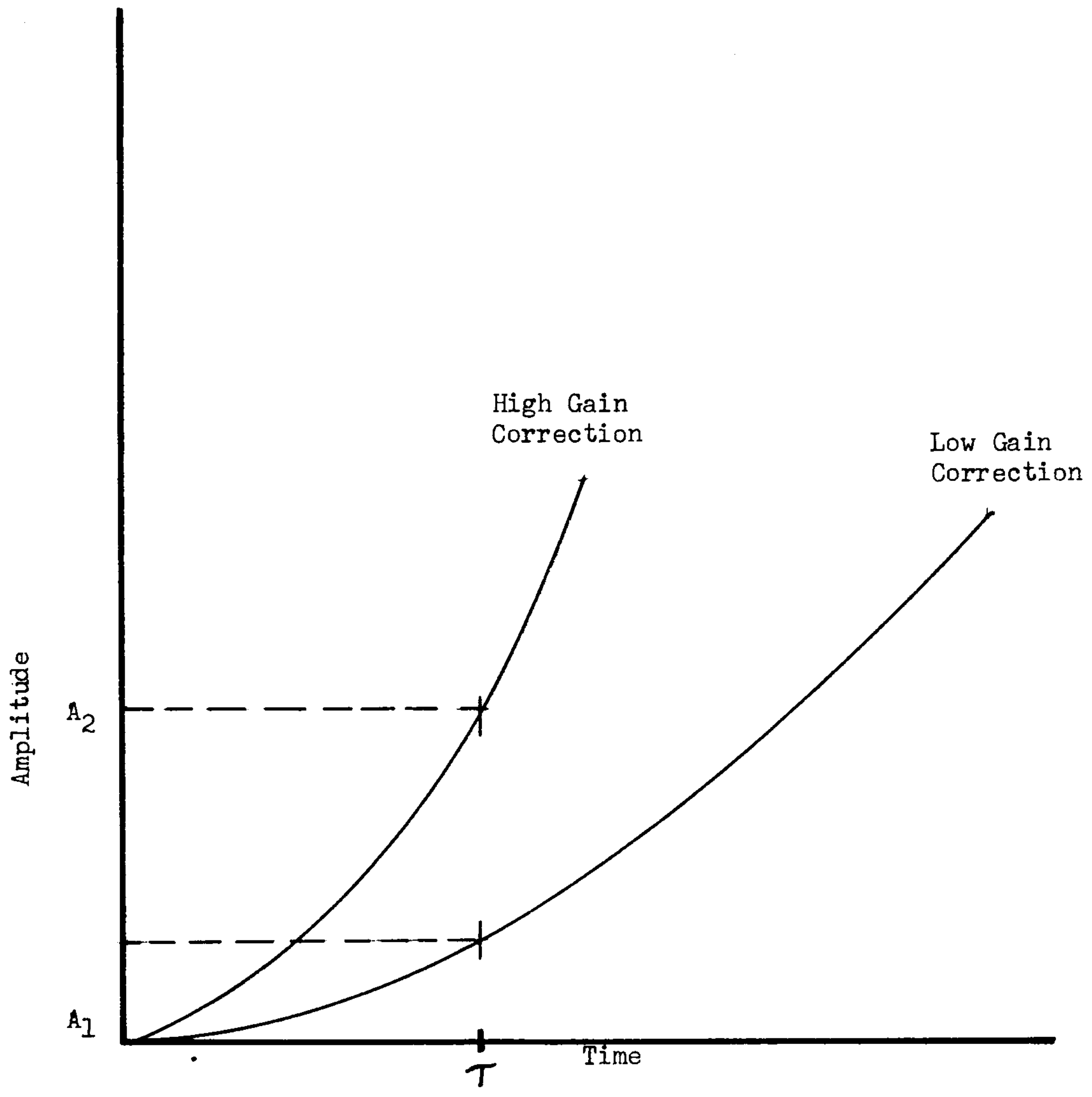


Figure C4

Output pattern for an integral filter in response to a ramp function. The difference A_2-A_1 represents the reduction in error during the lag time τ achieved by the increase in system gain.

APPENDIX D

SIDE-STICK CONTROLLER EVALUATION

The longitudinal stick force and displacement per unit acceleration for the side arm controller are:

$$\frac{f_s}{\Delta N_L} = 0.25 \text{ lbs/g}$$

$$\frac{\delta_s}{\Delta N_L} = 0.14 \text{ in/g}$$

The lateral control gain was such to give .04 radians of aileron deflection per inch of control displacement.

During the installation and checkout of the side arm controller, it was discovered that it was very difficult if not impossible to make longitudinal control inputs without making inadvertent lateral inputs. This control coupling was attributed to the extremely light control forces necessary and the similarity of both longitudinal and lateral control force-displacement characteristics. The side arm controller was therefore modified by placing foam rubber around the control lever and inside the case so that the lateral control forces were essentially doubled while the longitudinal forces were only slightly increased due to increased friction. The electrical dead band in the lateral mode was also increased to further prevent the inadvertent lateral inputs.

TABLE D1

COMPARISON OF SIDE-STICK AND CENTER-STICK CONTROLLER SCORES

I. CONDITION 10L12

Variable	Center-Stick	Side-Stick
Pe	.540 deg.	.378 deg.
He	22.7 ft.	12.8 ft.
Hc	.28 sq.in.	.41 sq.in.
RMS St	.228 in.	.037 in.
N_L	.146 G (Peaks ±1.2)	.110G (Peaks ±1.2)
St F	6.95/min.	6.20/min.
Lag	.205 sec.	.094 sec.
Gain	.151	.115
HR	82.5/min	82.5/min.
RR	17.5/min	15.5/min.

TABLE D1 (CONTINUED)

II. CONDITION 10C1.2

Variable	Center-Stick	Side-Stick
Pe	1.69 deg.	1.52 deg.
Hc	36.6 ft.	22.7 ft.
Hc	.30 sq.in.	.27 sq. in.
RMS St	.344 in.	.072 in.
N_L	.155 G (Peak ±1.2)	.130 (Peak ±.9)
St F	5.68/min.	8.03/min.
Lag	.116 sec.	.160 sec.
Gain	-	.133
HR	91.0/min.	87.5/min.
RR	18.5/min.	18.0/min.

III. CONDITION 20L1.2

Variable	Center-Stick	Side-Stick
Pe	1.00 deg.	.39 deg.
He	31.3 ft.	8.90 ft.
Hc	.35 sq.in.	.47 sq.in.
RMS St.	.404 in.	.036 in.
N_L	.292 G (Peaks ±2.0)	.231 G (Peak ±1.6)
St F	9.55/min.	5.10/min.
Lag	.294 sec.	.072 sec.
Gain	.294	.160
HR	86.5/min	81.5/min
RR	16.0/min	18.0/min

TABLE D1 (CONCLUDED)

IV. CONDITION 20C1.2

Variable	Center-Stick	Side-Stick
Pe	1.78 deg.	1.46 deg.
He	34.5 ft.	13.8 ft.
Hc	.37 sq.in.	.18 sq.in.
RMS St	.483 in.	.062 in.
N_L	.2896 (Peaks ±2.0)	.2246 (Peaks ±1.4)
St F	11.18/min.	8.10/min.
Lag	.292 sec.	.088 sec.
Gain	.381	.131
HR	88.5/min.	81.5/min.
RR	19.0/min.	18.0/min.

NOTE: The symbols for variables are identical in meaning to those previously used.

TABLE D2

SIGNIFICANCE TESTS BETWEEN SIDE-STICK AND CENTER-STICK SCORES

Variable	t	d_f	p
Pe	4.000	7	$<.005$
He	4.214	7	$<.005$
Hc	-.159	7	-
RMS St	8.444	7	$<.0005$
N_L	5.949	6	$<.0005$
St F	.854	5	-
τ	2.352	4	$<.05$
K	1.946	7	$<.05$
HR	1.961	7	$<.05$
RR	1.890	7	$= .05$

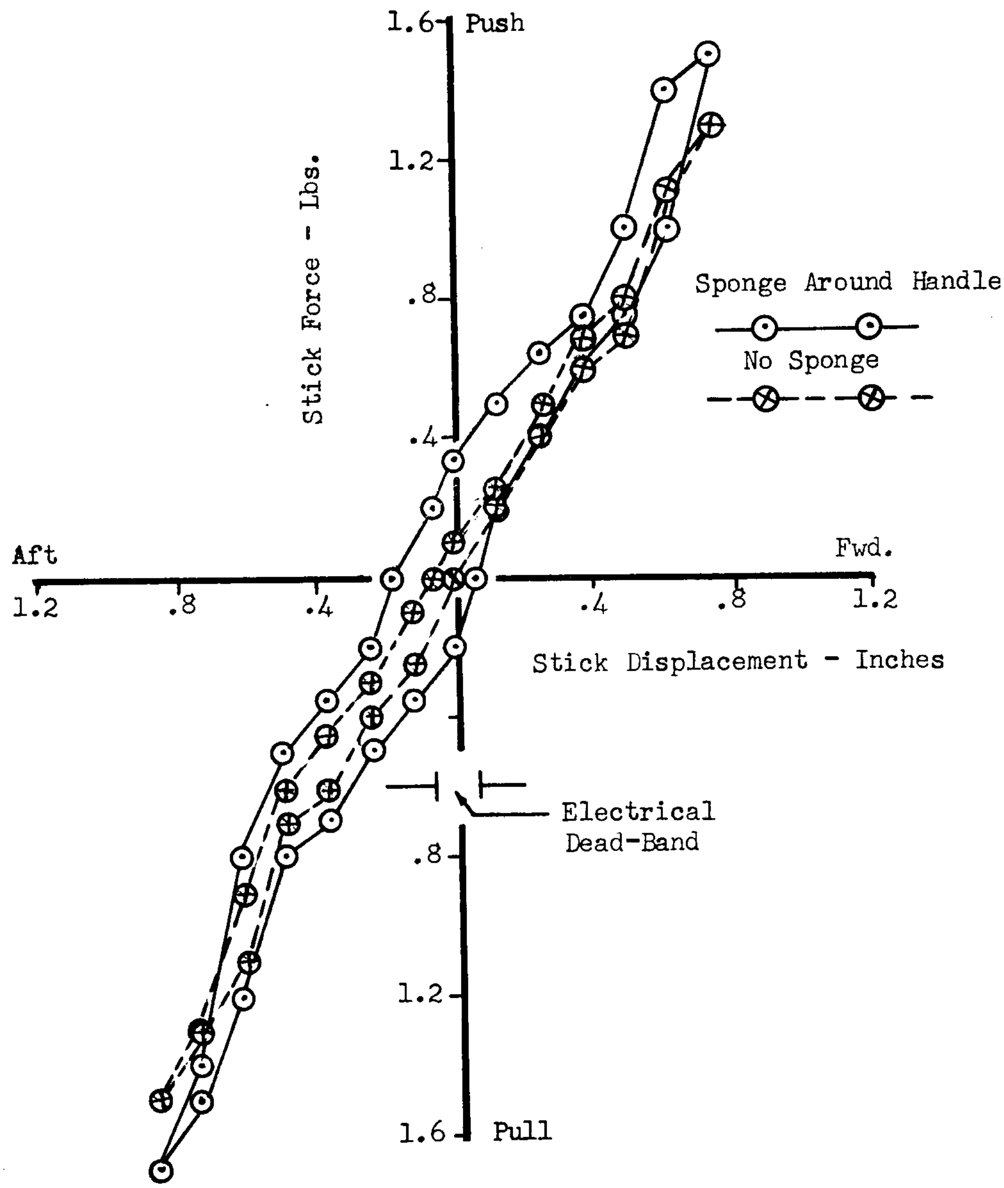


Figure D1
NASA Side-Stick Controller:
Longitudinal Force-Displacement Characteristics

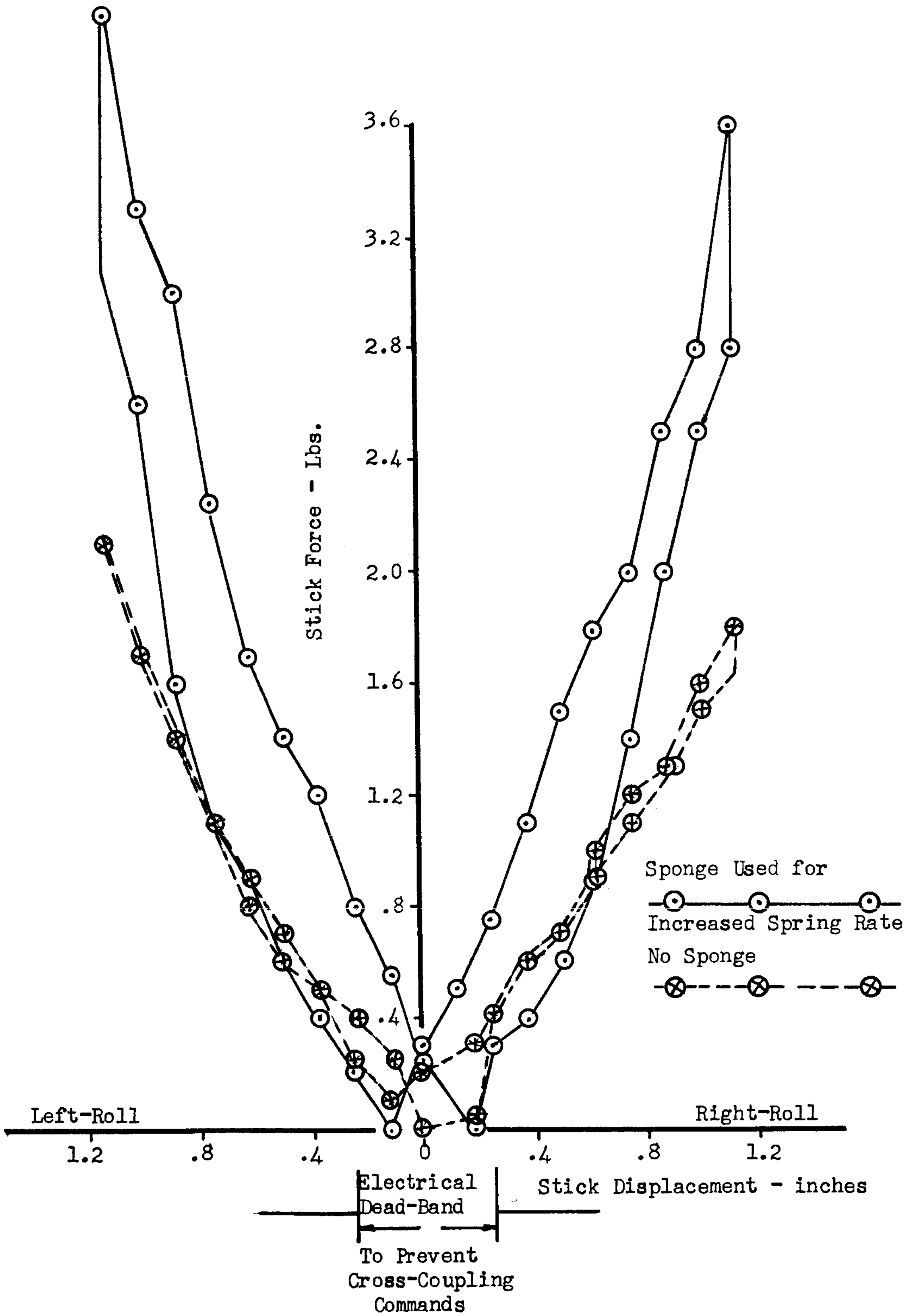


Figure D2
NASA Side-Stick Controller:
Lateral Force-Displacement Characteristics

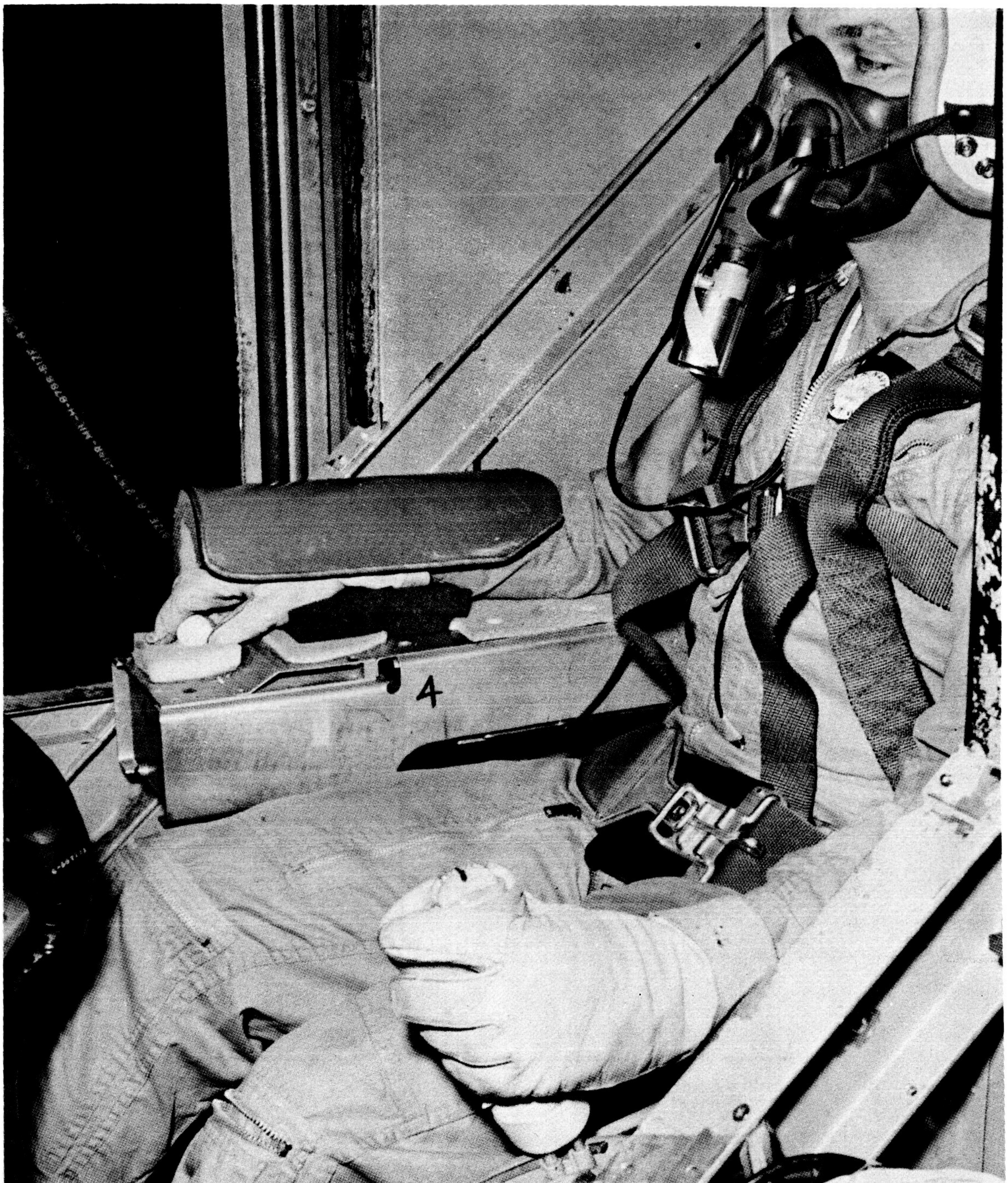


Figure D3
Position of side-stick controller in cockpit

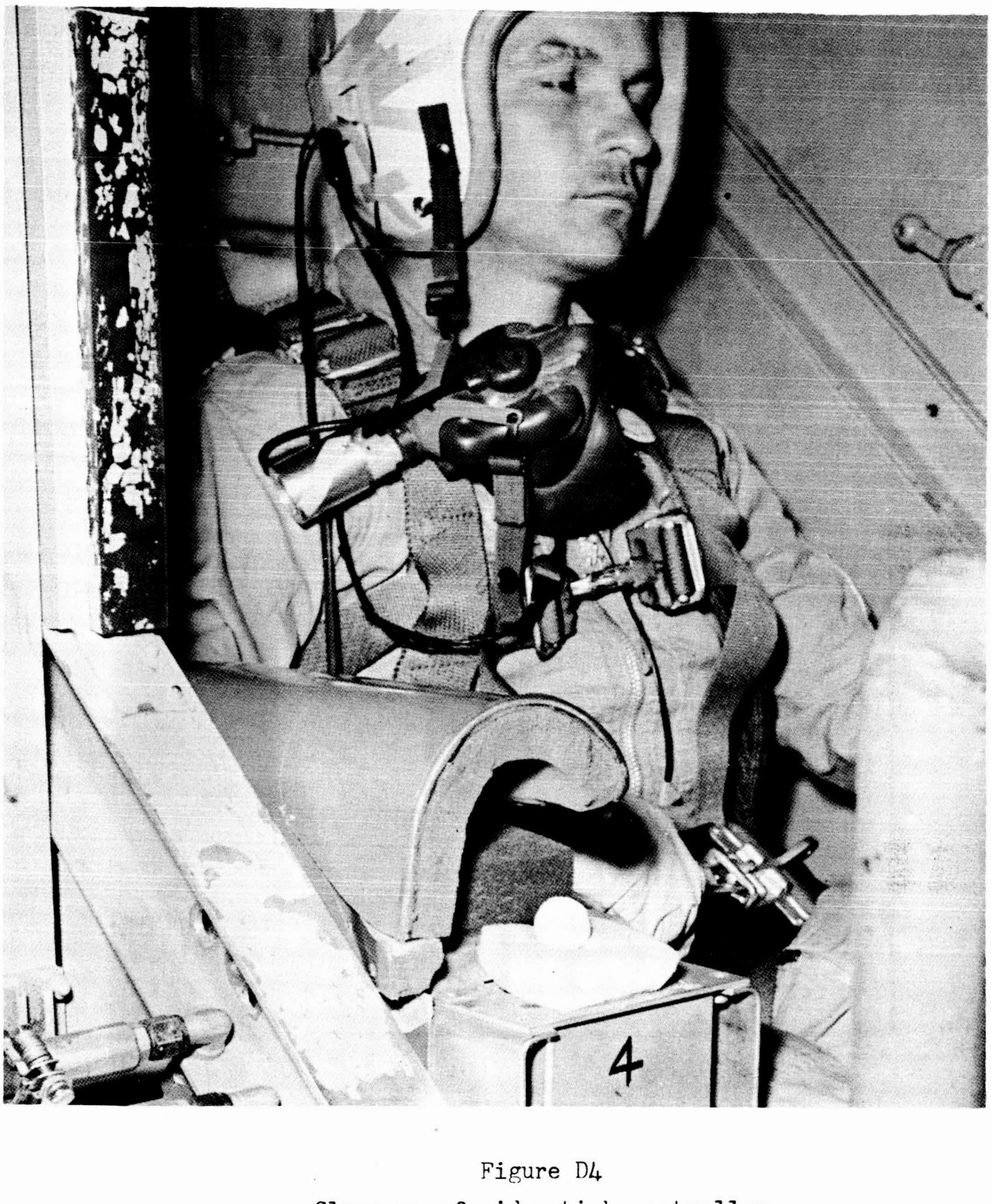


Figure D4
Close-up of side-stick controller

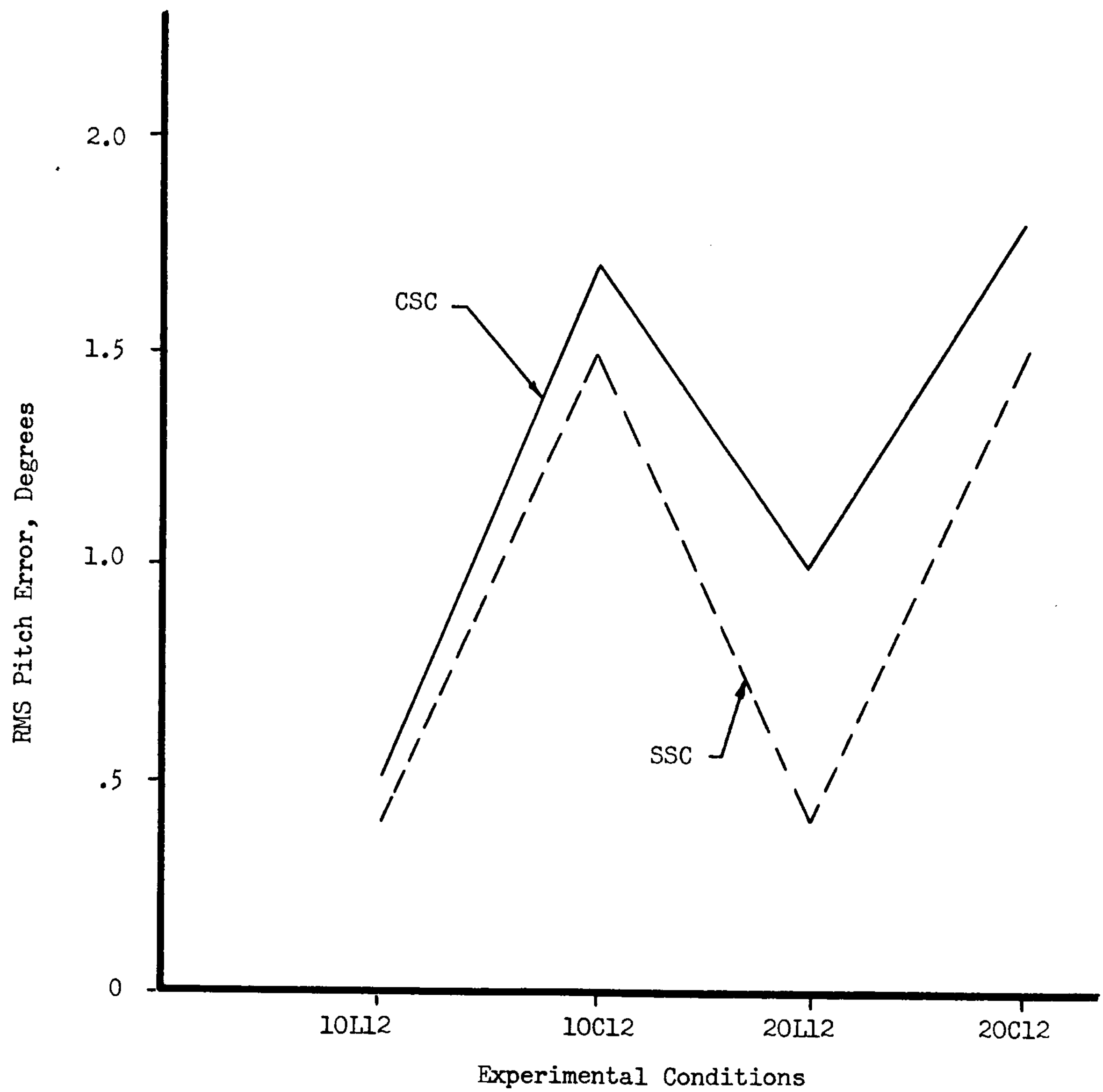


Figure D5
Side-Stick - Center-Stick Comparison
RMS Pitch Error

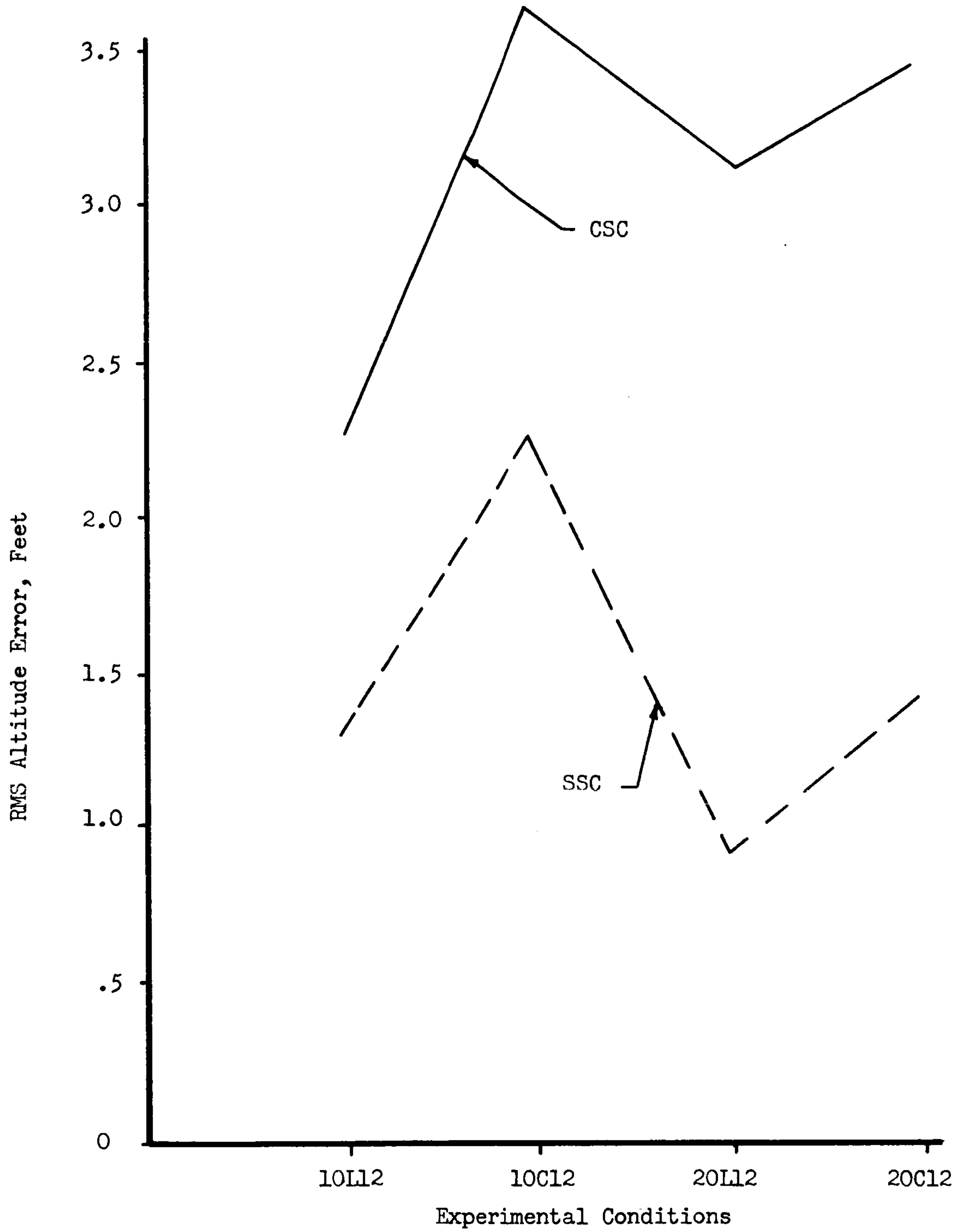


Figure D6
Side-Stick - Center-Stick Comparison
RMS Altitude Error

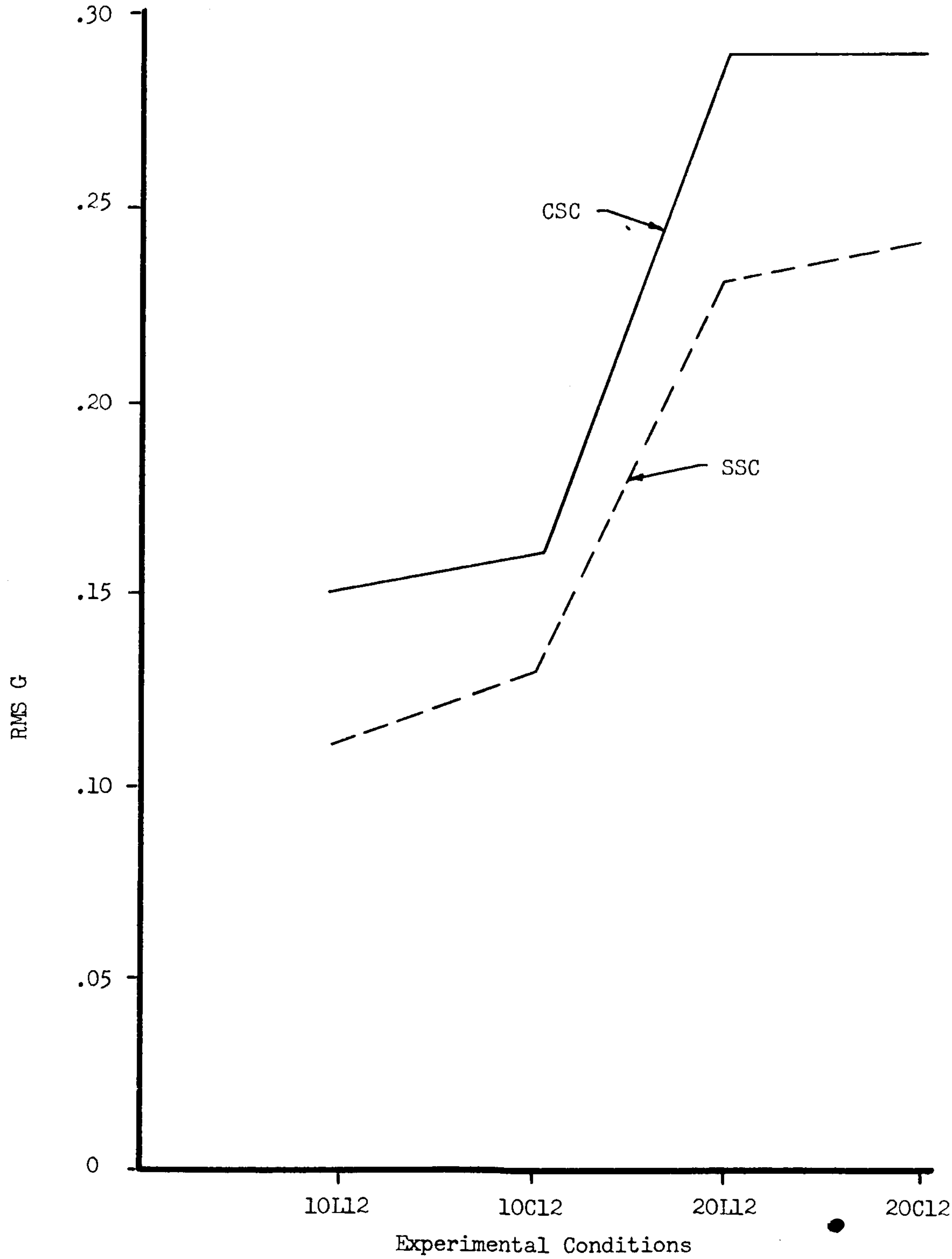


Figure D7
Side-Stick - Center-Stick Comparison
RMS G

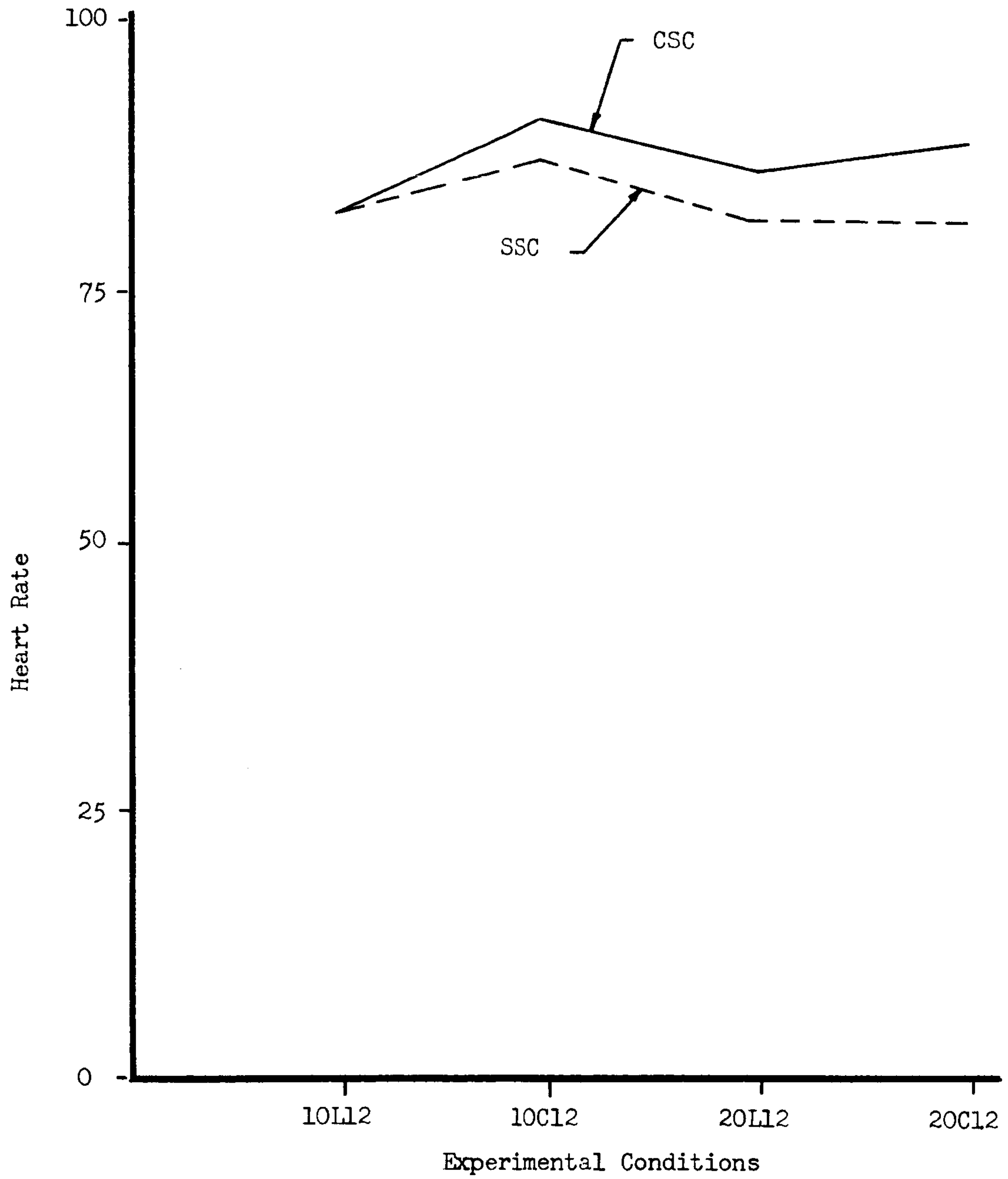


Figure D8
Side-Stick - Center-Stick Comparison
Heart Rate

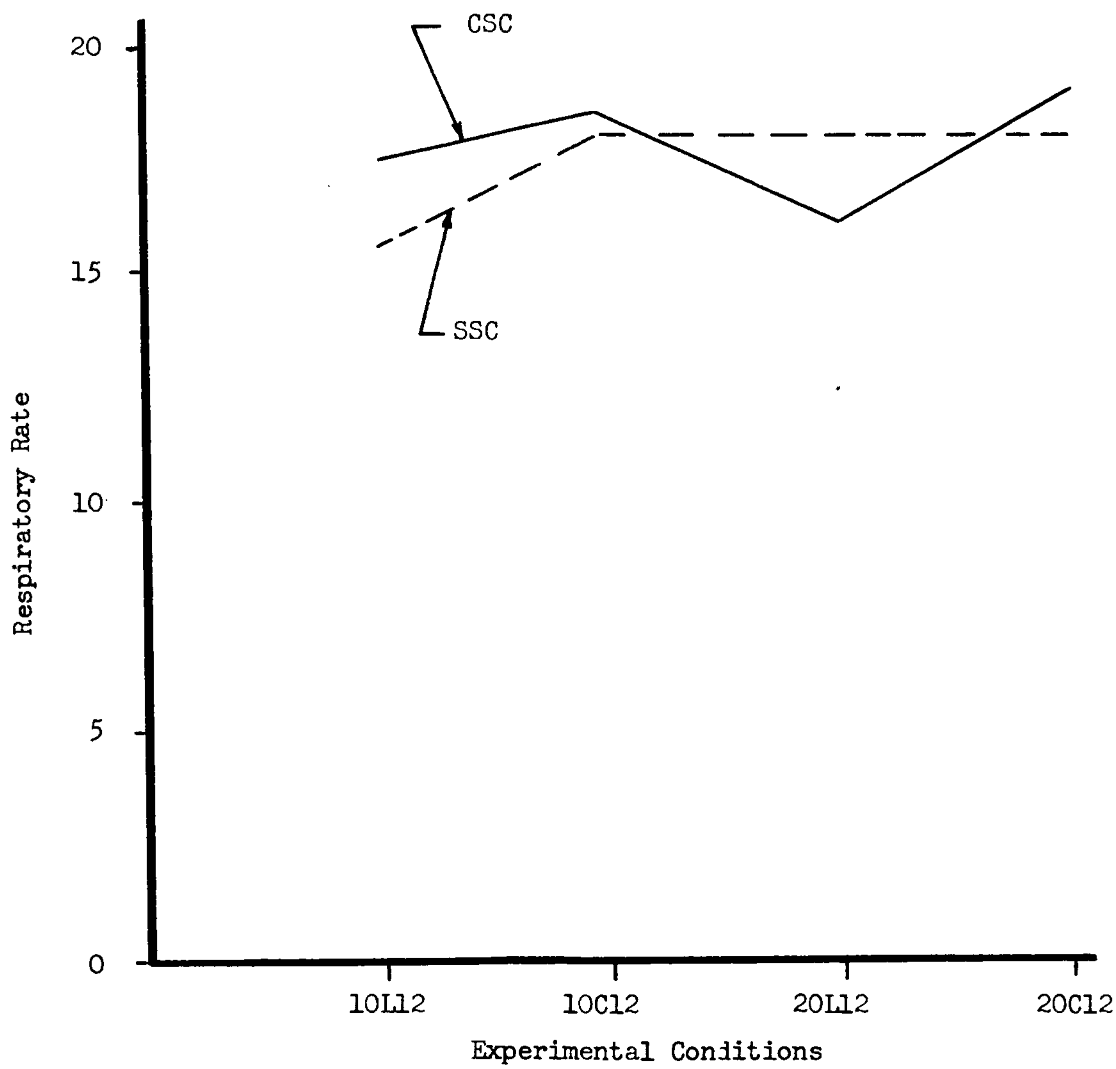


Figure D9
Side-Stick - Center-Stick Comparison
Respiration Rate

APPENDIX E

PILOTS'S COMMENTS

Comments When Center-Stick Control was Used

Pilot 1

Cockpit ventilation not too good. (A ventilating fan was later installed.) The (electrode) patches may be irritating after a week or two. You get extra altitude error from failure of pitch-altitude hook-up....probably at the beginning of the tape. Gust and terrain tape should be stopped before the end to get rid of transient signals. Because of control system problems and terrain, performance may be worst at the 2'/sec gust level. There is an undesirable shifting force deadband. The washout circuit is gust-like and at a higher rate than the rate (2 ft/sec gusts) that you put on. The 10 ft/sec gust level is better (than the 2 ft/sec level), but the washout circuit is still noticeable for large stick inputs. The washout problem at 2 ft/sec is worse with contour terrain than with level (terrain) because of the smaller inputs in level flight. The 20 ft/sec gust level gives a pretty rough ride.

Pilot 3

Comments of this pilot are those made in his trip report:

Lateral force gradient is too high relative to pitch force gradients; resulting in poor control feel harmony. The fact that rudder pedal forces and deflection have no effect on control of the simulator adds to this deficiency.

No aileron trim feature is provided and constant pressure must be held to maintain a constant bank angle. This is not a good simulation of bank control for a well designed airplane. In a flying task where instrument integration is used for airplane control, lateral stick forces should not be required to maintain a desired bank angle. Once a bank angle is established, stick forces should be trimable to zero force. In the simulator this deficiency resulted in a roll oscillation when attempting to maintain an aim bank angle and cross check pitch control. Pitch control information was presented on a cathode ray tube, bank angle and heading information was presented on an attitude indicator. The combined effect of poor lateral control, and not having pitch command information on the attitude indicator resulted in reducing bank angle to 10 to 20 degrees, when turning to a command heading, rather than the recommended 30 degree bank angle. For bank angles of greater than 20 degrees, simulator control was unsatisfactory.

The instrument panel layout was very poor because the off-center grouping does not afford good cross check reference and increases instrument integration learning time. A relocation of instruments was suggested to provide better functional grouping.

Gust simulation was very good. The simulated gust conditions felt very much like actual turbulence which I have experienced. With the higher gust loads, visual acuity is very much reduced. Focus in depth, I think, is maintained; but "caging the eyeballs" to discriminate accurate visual cues of small magnitudes gets progressively more difficult as gust intensities are increased. At the higher level gust of 20 ft/sec, I was flying a mean displacement error and accepting a blurred visual target as the result of small rapid movements due to gusts and not as a loss of visual focusing.

Flailing of the arm, holding the control stick, introduces random stick inputs when flying at the higher gust loads of 20 ft/sec. These random inputs result in the simulator departing from the desired aim flight conditions of terrain clearance and heading. I expect that there is some limit of gust intensity where the task of maintaining a terrain clearance and aim heading becomes impossible. The gust level intensity where this may occur depends on the airplane and the pilot; and when encountered the only corrective action possible is to depart that area of gust activity, if possible.

The flying task with gust load conditions other than 20 ft/sec was neither difficult or fatiguing, but rather very boring. Even at the gust load condition of 20 ft/sec, though much more difficult, the task was still very boring. The boredom experienced was a result of flying a task which required very little creative or intelligent analysis, if any, for a very long time period. Pilot analysis to fly this simulator reduces to two very simple binary decisions. One is to go up or down, the other to turn left or right. Pilots control airplanes by analysis and integration of many more factors than just the solution of two simple binary tasks. Reducing the pilot tasks where creative or intelligent analysis is eliminated may result in a condition where, out of boredom, the pilot becomes sleepy or acquires a lackadaisical attitude or possibly one of complete disinterest. I kept recalling the fact that I was supposed to be flying at 500 feet terrain clearance, as a stimulus to try to maintain a high level of interest because of the potential danger associated with low level flying.

During the first few flights, I notices a blurring of vision after about 40 to 50 minutes of flying. It was analyzed that this reduced visual acuity was the result of a mild case of hypoxia and eye fatigue. Cause of the hypoxia was due to the oxygen mask modification to accommodate a pneumotochograph sensor. This modification filled the oxygen supply hose opening of the mask and no provision for unrestricted inflow of air was made. Therefore, exhaled breath accumulated in the mask and was not replenished by fresh air oxygen. This resulted in re-breathing exhaled air which had an oxygen content less than that of normal air. From the above analysis, it is evident that after some time period, for me about 40 to 50 minutes, there would be some symptoms of hypoxia.[4] Once this was recognized I was able to avoid the occurrence of hypoxia by lifting the mask off my face and hyperventilating about every 20 to 30 minutes. By taking this action, an improvement in performance was immediately evident.

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[4] There were no correlations of pitch and altitude errors with these subjective changes.

The eye fatigue mentioned above in the preceding paragraph resulted from continuous focusing on the instrument panel, a depth of about 36" from the seat reference line. I was able to reduce this fatigue a great deal by periodically glancing out of the cockpit at a far wall, about 25 feet away. An added contributing factor to eye fatigue is a result of the cockpit lighting. The entire cockpit and instrument panel was very black during the flight with only the test instruments illuminated. A few number of test instruments mounted on a black instrument panel did not provide enough visual activity to prevent me from experiencing some auto-kinesis of the instruments and pilot spacial disorientation. Again, I was able to eliminate this sensation by periodically glancing out of the cockpit at a far wall, even though the room was very dark.

The longitudinal short period dynamics and control characteristics of the simulator for this type of mission and for the conditions flown appear satisfactory. The terrain contour flown was one of rolling hills, and therefore any favorable comment must be restricted to this parameter and not extended to mountainous terrain.

The NAA G-Seat as a flight simulator for investigation of low altitude, high speed flight problems appears satisfactory within the limit of experiment objectives. The experiment objectives were to assess human capabilities and limitations in low altitude, high speed flight.

For possible future simulator studies, bank angle should also be commanded. In an actual situation, there is a minimum bank angle that would give a required maximum allowable turning radius to avoid a given terrain condition. This minimum bank angle should be commanded since any smaller bank angle would result in terrain impact.

The instrument panel should be painted grey and better cockpit illumination should be provided. This would more closely simulate an actual cockpit environment, reduce auto-kinesis of the instruments, pilot spacial disorientation and eye fatigue.

Use of a side stick controller for this type of mission should be investigated. With a properly designed arm restrainer and side stick controller, random inputs from arm flailing may be eliminated.

Pilot 4

Pitch indicatorof AAI helped very little in pitch control. Too little sensitivity for making pitch corrections. Thought so at first, but have now learned to use it. Scanning important to maintain a closed control loop. This is a realistic instrument flying task. Flies like a plane, in that lift has to be used in a turn. When rolling into a turn, you lose altitude and have to add back pressure on the stick to maintain altitude. As in normal instrument flying, the AAI is the primary transition instrument; it is the primary instrument to monitor. Can minimize apparent He in turns by keeping turn rates low or bank less than (your recommended) 30 degrees. I find 15-20 degrees gives better control of terrain task while turning. Pitch roll quite pronounced. Must have a lot of aileron yaw. Feel system pretty sensitive for this task. More a pressure than a displacement system. Can use sound cues from hydraulic fluid sounds (in level flight). Link trainers do this. G-seat results will be conservative. Things get blurred at highest 10 ft/sec runs. At 20 ft/sec, blurring is consistent and constant. Contour (terrain) is harder to fly than level (terrain). The 10 ft/sec gust level is not particularly fatiguing. The 20 ft/sec (gust) level detracts from performance two ways: visual acuity decreases due to head movements, and involuntary stick movements (are greater). The 20 ft/sec gust level is more fatiguing than the others, but it is not, e.g. twice as fatiguing as 10 ft/sec.

Pilot 5

Fatigue doesn't come from effort; it is more like boredom; the eyes become unfocused; it's like driving fatigue. Used to the flying qualities now (after the first flight; this showed up clearly on the performance records). Too much (control stick) friction laterally, also longitudinally. The tracking's fairly easy. It works better when the rate of climb (indicator) isn't given too much attention. I started to drift off the last 15 minutes (after a run at 2 ft/sec). Gust is simulated quite well, but the aircraft feel isn't like a real airplane, both laterally and longitudinally, due to the breakout friction and control movement. From my experience, real aircraft seem to encounter between 2 and 10 ft/sec gusts at low altitude most of the time.

Pilot 6

(The task) takes constant supervision because flying qualities are poor. Not that it's hard to fly; it just needs constant supervision. I believe performance stayed constant throughout the run. Not too tiring. R/C too sensitive, especially if it drifts off. It indicates more than it really is. Plane does not feel damped enough in roll; it tends to over-control in rollout. This feeling is intermittent. No harder to control at 20 ft/sec than 10 ft/sec (gust levels). Might do a little worse at 2 than at 10 or 20 ft/sec because of boredom at 2 ft/sec. Have learned to compensate for large breakout force (after a few flights).

Pilot 7

Force gradient and breakout forces too great. The force gradient (when the) nose (is) down is greater than the force gradient when the nose is up. The plane is neutrally stable (the airspeed was constant). Flights not tiring. Difficult to fly, but could get used to it. Did not improve during the mission, but did improve from the first day (this comment was made on the second day). Am learning to fly this simulator. It's harder to stay amused at 2 ft/sec than 10 ft/sec. This gust level (20 ft/sec) actually better than the lower levels, because it keeps the pilot busy...no boredom.

Pilot 8

Comments of this pilot were made in his report on the study, and are listed as they are given in this report.

Aircraft and Gust Simulation

The aircraft motion in heave resulting from small to moderate amplitude control application was well simulated. The large amplitude stick inputs were quickly washed out and this resulted in lower G-seat response than would be normal under actual conditions.

The aircraft responses were clearly visible on the AAI and they appeared to correspond closely to anticipated motion in 5 degrees of freedom.

The control feel in pitch had some effect on tracking accuracy. At low gust levels it reduced the control accuracy, while at high gust velocities, by masking some of the feedback from body motion, it tended to improve mission tracking.

The simulationof gust response at high speed and low level was very good in amplitude and frequency and closely resembled actual flight conditions experienced under these conditions.

The Mission

A night mission on partial instrumentation was simulated with a realistic display of a limited task. In measuring pilot's performance with the view of possible extension of findings to the future mission, an allowance must be made for the comparative simplicity of the task as presented in the simulator. In a practical mission of this kind, there will be several other factors which will tend to complicate it. In our case the terrain following task, being at times more severe than could be negotiated in practice, tended to off-set this problem to some small degree.

Environmental Effects

An adequate ventilation of the cockpit area in the G-seat was essential to ensure that its lack did not influence experimental results to a larger degree than some of the controlled variables in the mission. Pilot's isolation from external disturbances, while on the task, is important for similar reasons.

Psychological Considerations

The fatigue experienced during the course of runs appeared to have its origin mainly in the eye fixation resulting from continuous eye convergence onto the display panel and the need for fully focused vision at closed and fixed distances.

Unless the eyes were allowed to rest for a minute or so, the "switch-offs" were experienced which resulted in a momentary loss of tracking performance. The effect of these on the RMS height error and RMS pitch error were very serious and care should be taken not to interpret these as indications of general physical fatigue, but rather as area localized fatigue.

The "switch-offs" appeared to be reinforced by jarring of the eyes in heavy gust levels.

The experience of above mentioned effects may be a very serious factor in concentrated long duration mission of LAHS category to a much greater degree than previously recognized in the instrument flight under IFR. The proximity of ground constitutes the dangerous aspect accompanying this mission. There appears a very urgent need for thorough investigation of this condition with the view of overcoming its effects, if, in fact, this type of mission is envisaged.

A superficial examination of other pilots's records clearly indicated periods of switch-offs similar in effect to those experienced subjectively by the writer.

On the basis of subjective view on performance of this mission, it appeared that, motivation followed by technique of flying and individual physical make-up (in that order) at similar all-round level of flying experience, might account for the difference between individual performances in the same type experimental runs.

Comments When Side-Stick Control was Used

Pilot 5

The job is much easier (with the side-stick) than with the center-stick. Would like to see different spring constants fore and aft. Better position is needed for the controller; it could possibly be swiveled so it fits the angle of the hand.

The previous stick was not too good. Because of friction and the break-out forces, it was hard to get precise movements. The side-arm is better than the center-stick, but probably not as much as the records show. The side-stick is very easy to catch on to. My arm didn't get tired in 1 1/2 hours; I was quite comfortable.

The fatigue (in both center-and side-stick flights) is like driving fatigue. It varies in onset. Sometimes it doesn't appear at all, sometimes after 10 minutes. But, generally, it sets in during the last half hour.

Pilot 6

Much more easy and relaxing than the center stick. No noticeable arm fatigue. I was tenser on the knob at the beginning; held it looser after awhile. (After first flight with the side-stick).

Arm became tired after awhile due to keeping it in one position for a long time. You should be able to move it around to ease cramped muscles. I was wide awake today, but yesterday I was very tired and began dozing off after a half hour or so. This might explain the increase in He that we talked about.

The side-stick is probably more susceptible to fatigue before flight, that is, when you're tired to begin with. Boredom is more of a problem (than with the center-stick), maybe because of a lack of things to do and the high degree of relaxation. I like the side-stick in general, it's quite an improvement over the center-stick. This may be due, in part at least, to the fact that the feel of the center-stick was not too good.

Corrections are much easier to make with side-stick. There is less coupling between roll and pitch. There are fewer inadvertent stick inputs in gust due to the arm being cooped up. The restraint is not uncomfortable, but it probably would be redesigned if it were to be made operational. My arm was a little sore after flight, so there is some discomfort. Maybe the whole rig could be on a swivel. The sponge under the knob (on the side-stick) is of little value.

GLOSSARY

Symbol		Unit
f_n	undamped natural frequency of airplane	cycles per second
Fd	short period longitudinal dynamics lateral directional undamped frequency	cycles per second
F_s	control stick force	pounds
g	acceleration of gravity	32.2 feet per sec.^{2}
h	altitude	feet
h_t	terrain altitude	feet
K_1	pitch error scaling constant for CRT	
K_2	altitude error scaling constant for CRT	
M_n (or M)	Mach number	
M_q	pitch damping dimensional derivative	1/second
M_α	pitch control dimensional derivative	1/second^2
w_g	vertical gust velocity	feet per second
δ_s	control stick displacement	inches
T2.5	terrain pitch at a point 2.5 sec ahead of the airplane	
RMS	root mean square	
lp	distance from pilot to C.G. (lp = 25 ft)	feet
ζ	damping ratio - longitudinal short period	
ζ_d	damping ratio - lateral directional	
$RMSn_z$/RMSwg	gust sensitivity factor	g/foot/second
ω	frequency	radians/second

Symbol		Unit
N_1	normal load factor at pilot	
ω_N	undamped natural frequency of airplane short period longitudinal dynamics	radians/ second
ω_{N_d}	lateral-directional undamped natural frequency	radians/ second
ω_ϕ/ω_d	roll control coupling parameter	
V_o	forward velocity	feet per second
G	multiple of normal force of gravity	non-dimensional
Θ	pitch angle	radians
ϕ	roll angle	radians
ψ	yaw angle	radians
β	sideslip angle	radians
α	angle of attack	radians
δ_e	longitudinal control surface deflection	radians
δ_A	lateral control surface deflection	radians
He	altitude error	feet
Pe	pitch error	degrees
Hc	heading error	degrees
RMS St	root mean square of longitudinal control stick displacements	inches
St F	frequency of control stick movements	minutes
τ	pilot's lag	seconds
K	pilot's gain	radians/ inch error on CRT

Symbol		Unit
$\in$	integrated total error	square inches
HR	heart rate	beats/ minute
RR	respiratory rate	expirations/ minute
df	degrees of freedom	
SS	sum of squares	
MS	mean squares	
F	F-ratio	
p	confidence level	
σ	standard deviation	

NASA-Langley, 1964 CR-63